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Application of ash and slag waste from coal combustion in the construction of the earth bed of roads

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Abstract. More than 1.5 billion tonnes of ash and slag waste from thermal power plants have been accumulated in the RF. The most promising direction of reuse is construction and repair of roads. The most material-intensive direction is the construction of earth bed. The aim of the study is to expand the practice of using ash and slag mixtures from thermal power plants for the construction of roadbeds in continental and polar climate. In order to achieve the goal set in the work the ash and slag mixture from different ash dumps of Irkutsk region was sampled. Ash and slag wastes can be considered as technogenic soils and classified according to GOST 25100 as gravelly sands and dusty sands. Ash and slag mixtures do not possess cohesion, have low values of internal friction angle, high porosity of particles and low specific weight, and small frost heave deformation. To evaluate the efficiency of ash and slag mixtures application in the structures of the roadbed of roads the design and construction of the roadway and the roadbed on the section of the road in the Irkutsk region was carried out. The technology of works on construction of earth bed layers from ash and slag mixtures is similar to the technology of erection of layers from soils. The constructed construction of road with earth bed from ash and slag mixtures has operational characteristics not lower than the construction of the adjacent road section with earth bed from local soils. Ash and slag mixtures can be used for construction of earth bed layers practically without restrictions.

Keywords: ash and slag mixtures, earth bed from ash and slag mixtures, technogenic soils, roads

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1. INTRODUCTION

More than 1.5 billion tonnes of ash and slag wastes from thermal power plants (TPP) have been accumulated in the RF [1] and their amount is constantly growing. Only in the Irkutsk region 1.3 million tonnes of these wastes are generated annually.

Under these conditions, their reuse is of particular importance. The most promising area of reuse is the construction and repair of roads. This is due to the fact that a large amount of materials and soils are used in the construction of roads.

Different countries have different classifications of ash and slag waste [2]:

- Coal Combustion Products (CCP) or Coal Burning Bound-products (CBBP);
- Coal Combustion Residues (CCRs);
- Coal Utilization By-Products (CUBs)$
- Ash and Slag (Coal Ash);
- Fly Ash (FA);
- Class F Fly Ash (FFA) is produced from anthracite or bituminous coals (<10% lime). The sum of SiO2, Al2O3 and Fe2O3 is more than 70%$
- Class C fly ash is produced from brown coal or sub-bituminous coals (>20% lime) Sum of SiO2, Al2O3 and Fe2O3 more than 50%)4
- Brown coal fly ash (BCFA)$
- Pulverized fuel ash (PFA);
- Boiler slag from boilers with solid ash removal (bottom ash – BA or furnace bottom ash – FBA);
- Boiler slag from boilers with wet ash removal (BS)$
- Ash and slag mixture (ASM) – a hydrated mixture of ash and slag formed from bottom ash suspension;
- Oil shale ashes (OSA) – a waste obtained at thermal power plants using dispersed oil shale as a process fuel.

In RF, it is customary to divide ash and slag waste into:

1. Fly ash.
2. Fuel slags.
3. Ash and slag mixture.

The properties of these wastes are studied by various authors and differ depending on the type of fuel burned, the method of combustion and the method of waste storage. [3-6].

Various scientists have investigated the possibilities of ash and slag waste application [7-9]. These wastes can be effectively used in various building structures [10-11], for backfill [12], in compositions of stabilized soils [13-14], and fly ash can be effectively used as a self-sustaining binder [15-17] for stabilizing the soils of building foundations [18] and the soils of the roadbeds of highways [19-21].

Also, waste from thermal power plants can be effectively used in combination with other materials [22]. The paper [23] presents the results of studies of the effect of fly ash, lime and polyester fibers on the compaction and strength properties of swelling soil. The paper [24] presents studies of the physical, mechanical and chemical properties of solid biomaterials and raw fly ash from brown coal and their combination for use in road structures. The paper [25] presents a study of the effect of the combined use of fly ash and sawdust on the properties of swelling soils. The paper [26] presents an analysis of the effect of fly ash and lime on increasing the shear strength of clay. The paper [27] presents methods for selecting the compositions of soils stabilized with lime. The paper [28] presents a study of the effect of calcium bentonite clay and fly ash on the stabilization of organic soil. The results of a study of the combined use of cement and fly ash are presented in [29]. The results of the development of an inorganic binder based on fly ash and fluorogypsum are presented in [30].

Despite the available works, the use of ash and slag wastes from TPPs in road construction in the RF is insignificant. Especially it concerns the territories with polar and continental climate. Such areas are characterised by low duration of the construction season, high requirements for frost resistance and resistance to frost heave. Experimental works in these areas are practically absent.

The most interesting from the point of view of large-tonnage use is the use of ash and slag waste for the construction of the roadbed of roads. In this case, ash and slag waste is considered as man-made soil, and ash and slag dumps as large man-made deposits. The use of ash and slag waste for the construction of the roadbed does not require preliminary technological preparation (grinding, roasting, screening, etc.).

Taking into account the above stated in the work the aim is to expand the practice of application of ash and slag mixtures of TPPs for construction of road subgrade in continental and polar climate conditions.

2. METHODS AND MATERIALS

To achieve the goal set in the work, sampling of ash and slag mixture from ash dumps of the Irkutsk region was carried out (Fig. 1). The total volume of accumulated ash and slag mixtures in ash dumps of the Irkutsk region is more than 87 million tonnes.

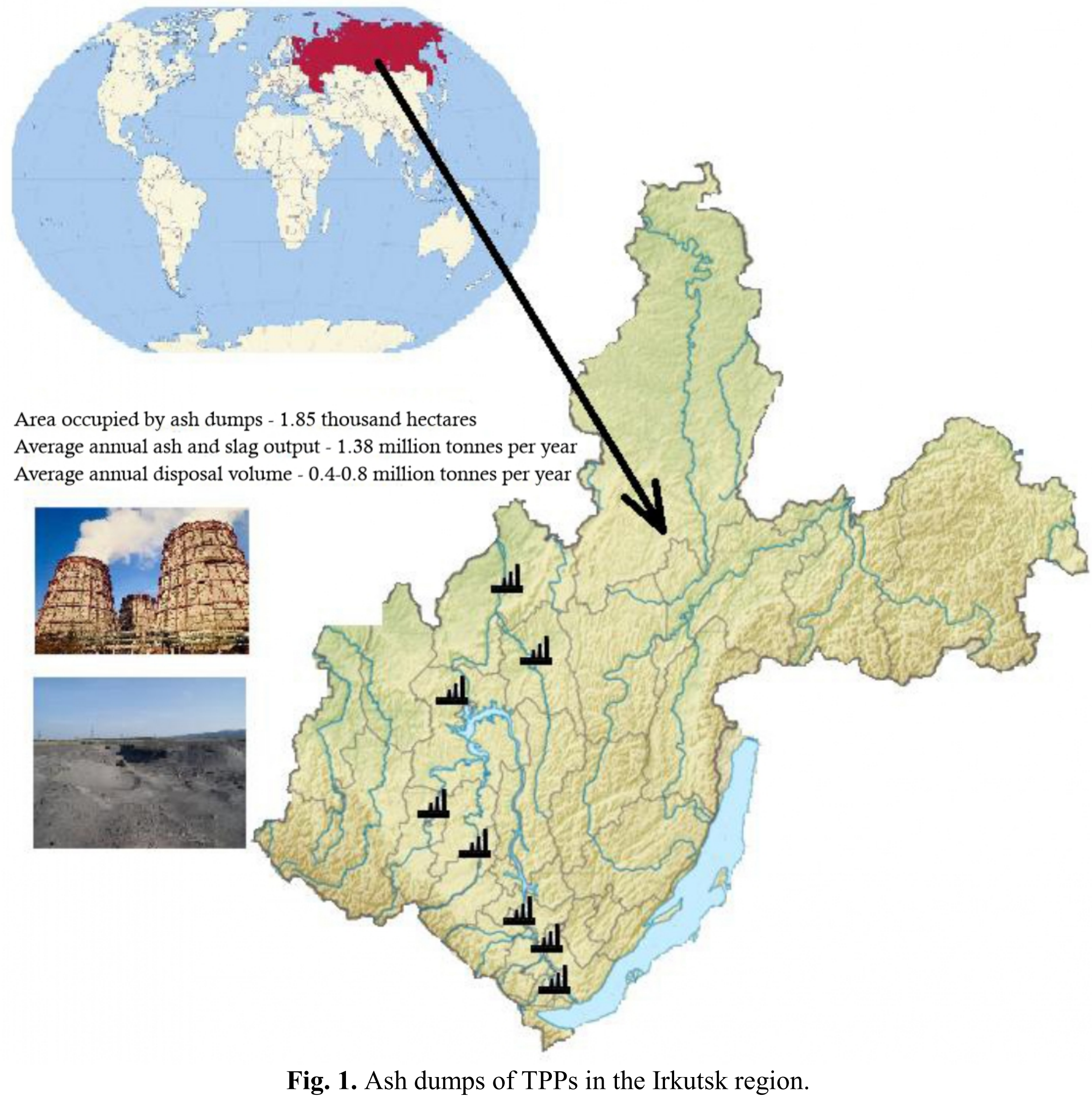

Fig. 1. Ash dumps of TPPs in the Irkutsk region.

The selected samples are summarised in Table 1.

Table 1. Laboratory samples of ash and slag mixtures from TPPs.

Sample	Name of TPP
1	TPP-6
2	Heat sources and heating networks section TPP-6
3	TPP-9
4	TPP-10
5	TPP-11
6	Novo-Irkutsk TPP
7	Shelekhov section of the Novo-Irkutsk TPP
8	Ust-Ilimsk TPP
9	Novo-Ziminsk TPP

Determination of basic physical and mechanical characteristics of ash and slag mixtures was carried out by standard methods of GOST.

The following laboratory test methods were used to determine physical and mechanical properties of ash and slag materials and their classification:

- GOST 12536 “Soils. Methods of laboratory granulometric (grain-size) and microaggregate distribution”;
- GOST 25100 “Soils. Classification”;
- GOST 28622 “Soils. Laboratory method for determination of frost-heave degree”;
- GOST 310.2 “Cements. Methods of grinding fineness determination”;
- IRM 218.2.031 “Methodical recommendations on application of fly ash and ash and slag mixtures from coal combustion at thermal power plants in road construction”.
- GOST 25584 “Soils. Laboratory methods for determination of coefficient of hydraulic conductivity”.
- GOST 12248 “Soils. Determination of strain deformation parameters of frozen soils by compression testing”.

Particles of ash and slag mixtures are brittle and subject to crushing during compaction of roads layers. For quantitative estimation of particles crushing degree at compaction the crushing index is used, which is determined by calculation of average particle size before and after compaction and expression of crushing index as a percentage decrease between two average values of initial average size.

To quantify the degree of particle crushing during compaction, a crushing index is used, which is defined as the ratio of the weighted averages of the average particle size before and after compaction:

$$I = \frac{\sum a_i \cdot d_i}{\sum a_j \cdot d_j}, \quad (1)$$

где a_i, a_j – particle content of each fraction before and after compaction, respectively, %;

d_i, d_j – particle diameter before and after compaction, respectively, мм.

3. RESULTS AND DISCUSSION

Mineralogical composition of ash and slag mixture is given in Table 2 [31].

Table 2. Mineralogical composition of ash and slag mixture № 5.

Name of mineral	Crystalline phase content, %
Quartz	35
Mullite	15
Albite + microcline	10
Glass phase	50

Ash and slag mixture is an aluminosilicate material with 50% content of glassy particles of spherical shape.

Physical and mechanical characteristics of ash and slag mixtures are given in Table 3.

Table 3. Physical and mechanical characteristics of ash and slag mixtures.

Name of indicator	Laboratory samples								
	№ 1	№ 2	№ 3	№ 4	№ 5	№ 6	№ 7	№ 8	№ 9
Classification	dusty and gravelly sand	dusty sand	dusty sand	dusty sand	dusty sand	dusty sand	dusty sand	dusty and gravelly sand	dusty sand
Particle content <0,002 mm, %	6.70	5.60	8.60	-	2.40	2.50	4.90	5.00	-
Plasticity number	Non-plastic	Non-plastic	Non-plastic	Non-plastic	Non-plastic	Non-plastic	Non-plastic	Non-plastic	Non-plastic
Type of ash and slag mixture	fine-grained	fine-grained	medium-grained	medium-grained	medium-grained	medium-grained	fine-grained	medium-grained	-
Total residue on the sieve № 008, %	20.6		37.7-57	31.7	22.7	50.3	67.3	39.7	43.3
Specific surface area, m2/kg	245.8		201.7-266	199.8	221.2	236.5	212.3	247.4	340.2
Mass loss on ignition, %	13.77-15.4	1.34	0.52-4.76	0-3.00	0-14.45	0	0.75-1.49	1.13-5.50	2.73
Content of combustible substances	high	low	low	low	low to high	-	low	low and medium	low
Relative frost heave deformation	0.019	0.043	0.022	-	0.0005-0.039	0.020	0.038	0.0015-0.028	-
Bulk density, kg/m3	680-692	1060.00	740-1190	955.25-1010	950-1365.88	880-1430.78	610-832.10	1000.29-1170	740
Maximum density, g/cm3	1.17-1.70	1.38	1.17-1.19	1.17-1.8	1.21-1.62	1.30-1.73	1.03-1.11	1.58-1.88	1.10
Optimum humidity , %	15.98-37.64	26.69	26.81-29.66	24.14-28.81	10.36-17.07	20.92-30.16	36.92-46.4	11.97-18.59	36.40
Seepage coefficient at maximum density, m/day	0.04	0.07	0.02	0.04	0.12	0.04	0.06	0.03	-
Strain modulus, MPa		14.29	-		9.52	14.29	10.53	2.47	-
Angle of internal friction, °		17	-		22	23	14	1.49	-
True density, g/cm3	2.46	-	2.02	2.01	2.21	2.35	-	60.3	2.16
Average density, g/cm3	1.46	-	1.16	1.15	1.54	1.56	-		1.34
Porosity, %	40.6	-	42.6	42.8	30.3	66.3	-		62.1

Continuation of Table 3

Resistance against silicate and ferruginous decomposition	no fraction	no fraction	no fraction	no fraction	no fraction	no fraction	no fraction	no fraction	no fraction
Frost resistance of slag crushed stone	no fraction	no fraction	no fraction	no fraction	no fraction	no fraction	no fraction	2.47	no fraction
Content of clogging inclusions	Absent	-	Absent	Absent	Absent	Absent	-	1.49	Absent
Grinding index I	7.07	1.31	8.35	10.74	46.74	32.59	12.47	38.27	-

The particle size distribution is given in Table 4.

Table 4. Granulometric composition of ash and slag mixtures.

Laboratory samples	Sieve size, mm									
	20	10	5	2,5	1,25	0,63	0,315	0,14	0,05	less than 0.05
№ 1	0	18,51	31,42	38,98	51,94	68,28	74,69	78,18	84,46	100,00
№ 2	0	0,00	0,00	0,06	0,32	0,41	0,59	0,85	5,53	100,00
№ 3	0	0,99	2,28	3,78	5,93	8,17	11,34	20,96	50,67	100,00
№ 4	0	0,00	0,28	0,48	1,02	2,00	3,64	14,34	51,24	100,00
№ 5	0	0,00	0,00	0,03	0,09	0,33	0,97	3,10	23,82	100,00
№ 6	0	0,22	0,45	1,22	1,96	4,15	11,73	34,31	68,25	100,00
№ 7	0	0,27	0,55	0,79	1,09	1,49	3,64	22,29	78,28	100,00
№ 8	0	5,52	13,96	25,38	50,64	65,83	71,34	77,55	90,51	100,00
№ 9	0	0,61	1,69	2,07	2,84	4,16	7,28	17,40	42,17	100,00

As can be seen from the tables, ash and slag wastes can be considered as technogenic soils and classified according to GOST 25100 as gravelly sands and dusty sands. Ash and slag mixtures do not possess cohesion, have low values of internal friction angle, high porosity of particles and low specific weight and small frost heave deformation. According to the results of analyses of physical and mechanical properties it can be concluded that ash and slag mixtures can be used for construction of earth bed.

For estimation of efficiency of ash and slag mixtures application in constructions of the earth bed of roads the construction of road pavement and earth bed on a site of road R-255 “Siberia” (Fig. 2) has been carried out.

Road pavement structures are given in Table 5.

Table 5. Road pavement structures.

Material	Thickness h, m	Material	Thickness h, m
Hot dense asphalt concrete. type B. grade II (crushed stone M1000) according to GOST 9128-2013	0.05	Dense asphalt concrete of II grade. type B according to GOST 9128-2013 (crushed stone M1000)	0.05
Hot porous asphalt concrete of II grade (crushed stone M800) according to GOST 9128-2013	0.07	Porous asphalt concrete of II grade according to GOST 9128-2013 (crushed stone M800)	0.07
Crushed stone M1000 according to GOST 8267-93	0.40	Porous asphalt concrete of II grade according to GOST 9128-2013 (crushed stone M800)	0.31
Sand according to GOST 8736-2014	0.30	Sand according to GOST 8736-2014	0.30
Earth bed from ash and slag mixture		Earth bed from local soil	

In 2021. work was carried out on the construction of a pilot section of a motorway with an earthen roadbed:

from ash and slag mixture of TPP-10 (laboratory sample № 4) with a total length of 150 m;

locally sourced.

The technology of works on construction of layers from ash and slag mixtures is similar to the technology of erection of layers from soils.

1. Preparatory works. The preparatory works included breaking out works. clearing of brushwood and small woods and replacement of overwatered subgrade soils (Fig. 2).

Fig. 2. Erection of earth bed layers from ash and slag mixture.

2. Erection of embankment layers. Backfilling of the bottom layer on the prepared natural base was carried out on a “back-to-back” scheme by means of motor transport. The lower layer was levelled by bulldozers evenly across the entire width of the embankment.

On the basis of trial compaction the thickness of the compaction layer. the number of passes on one trail and the scheme of movement of compaction means were determined.

It is expedient to compact ash and slag mixtures by means of heavy vibratory rollers (smooth anvil and ground rollers). In this case the moisture content of compacted layers was close to the optimum (Fig. 3).

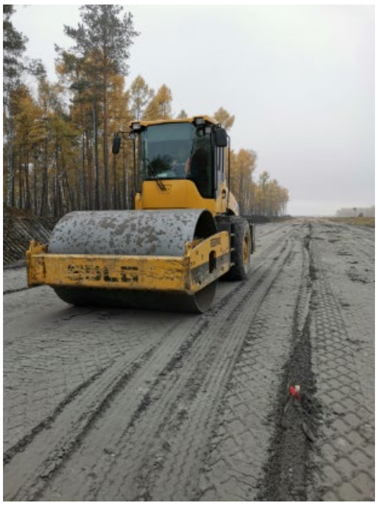

Fig. 3. Erection of earth bed layers from ash and slag mixture.

The embankment is arranged with 0.5 m extension on each side so that after the end of the embankment construction the uncompacted ash and slag mixtures can be cut off from the slope part of the earth bed. Then the slope surface was levelled. protective layers of soil-vegetation soil were arranged and grass was sown. The protective layer protects the slopes of the earth bed from water and wind and prevents the development of erosion processes.

During ash and slag mixtures dumping each layer was carefully planned with giving transverse slopes of 30-40‰.

3. Quality control of ash and slag mixtures was carried out in accordance with the requirements of CP 78.13330. IRM 218.2.031.

Operational control verified:

- density of soil at the base of the subgrade;
- moisture content of used ash and slag mixtures;
- thickness of the layers to be poured;
- achieved density in each technological layer after 50 m in 3 points along the cross profile;

At acceptance control it was checked:

- thickness and density of layers from ash-and-slag mixtures (Fig. 5);
- presence and quality of protective measures on slopes;
- thickness of the working layer;
- arrangement of drainage structures.

Also. during the construction of the layers. the elastic modulus was measured using the DINA-3M dynamic loading unit (Table 6).

Table 6. Results of elastic modulus measurements.

Location km/PC	Temperature. ºC		Measured elastic deflection. mm	Modulus of elasticity. MPa
	ambient air	layer		
PC2+00 (forward direction)	5.8	-	2.762	66.16
PC2+50 (reverse direction)	12.2	-	3.915	45.98

The performance of the constructed structure was monitored after construction was completed. The operation of the pilot earthwork structure is carried out under difficult conditions:

Increased moisture of the base and as a consequence increased moisture of the subgrade layers. which is due to the immediate proximity of the Celota Creek. as well as geological features of the terrain and lack of natural drainage.

The intensity of vehicle traffic is 13316 vehicles per day. The composition of the flow includes up to 45% of trucks weighing more than 25 tonnes.

The construction of the roads with the earth bed from ash and slag mixtures has operational characteristics not lower than the construction of the adjacent road section with the earth bed from local soils (Table 7).

Table 7. IRI pavement longitudinal flatness measurement results.

Measurement period	Requirements of CP 78.13330/ GOST R 50597	Construction with earth bed from ash and slag mixture			Construction with local soil subgrade		
		Straightforward direction	Reverse direction	Final value	Straightforward direction	Reverse direction	Final value
15.11.2021-16.11.2021	Up to 2.6	2.55	2.51	2.53	-	-	-
21.06.2022	Not more than 5.5	2.83	2.46	2.80	2.79	2.64	2.72

To assess the water-thermal regime of the subgrade. sensors for measuring soil temperature and moisture are installed in the body of the subgrade.

According to the results of measuring the temperature and humidity of the subgrade. a significant moisture accumulation of ash and slag mixture layers in comparison with layers from local soils was established (Fig. 4-5).

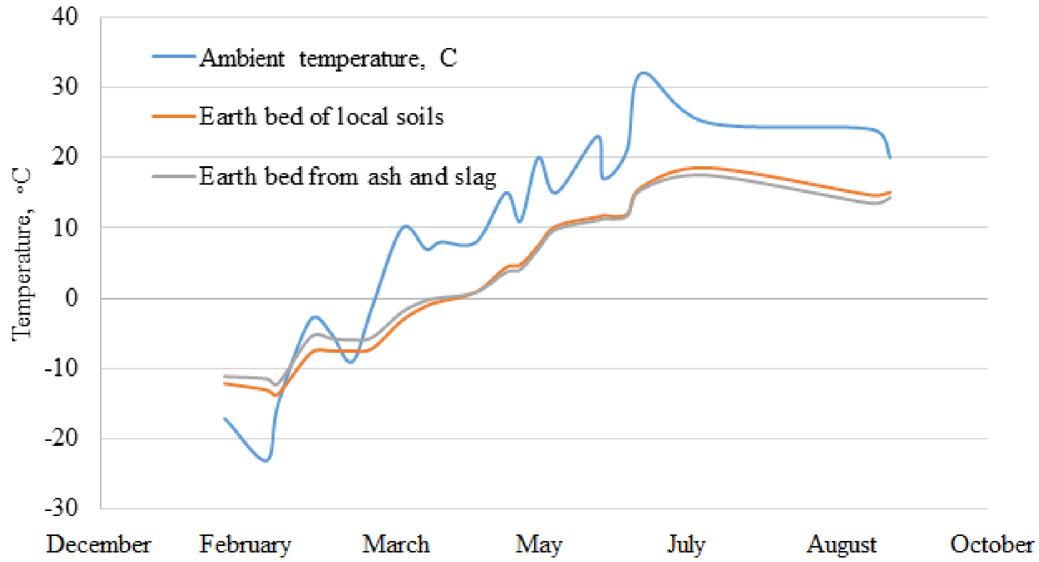

Fig. 4. Temperature measurement results of the experimental subgrade structure.

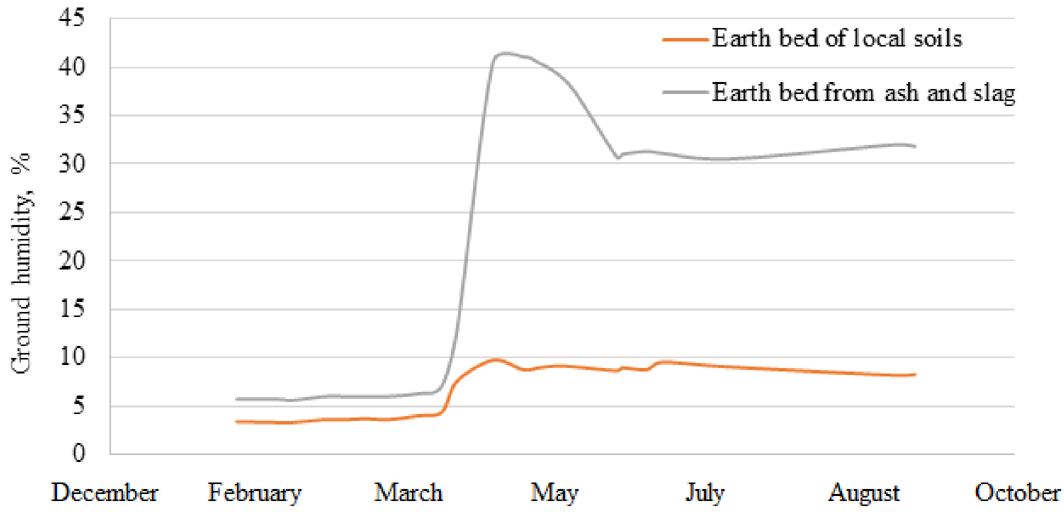

Fig. 5. Moisture measurement results of the experimental subgrade structure.

Besides. it is established that the temperature of ash and slag mixtures layers in the cold season is higher than that of local soils. which is explained by heat-insulating properties of ash and slag mixtures.

4. CONCLUSIONS

According to the results of research of properties of ash and slag mixtures of Irkutsk region it can be concluded that these materials can be used for construction of earth bed layers practically without restrictions.

Mineral particles of ash and slag mixtures have significant brittleness. which leads to a significant change in particle size distribution during compaction. For quantitative estimation of particles crushing degree at compaction the concept of crushing index is introduced. which is defined as a ratio of weighted average values of average particle size before and after compaction.

When carrying out works on construction of roadbeds from ash and slag mixtures it is necessary to take into account that:

- Ash and slag mixtures in the dry state have significant dustiness. Therefore. if it is necessary to temporarily store and store ash and slag mixtures in piles. it is necessary to carry out periodic moistening or cover with non-woven materials.
- Ash and slag mixtures by granulometric composition represent technogenic sandy soils. However. unlike sandy soils. compaction of overmoistened ash and slag mixtures is accompanied by squeezing out of the mixture from under the roller. increasing the width of the layer and reducing its thickness. Therefore. control of ash and slag mixture moisture content is especially important during earth bed construction.
- Ash and slag mixtures have low values of elastic modulus and angle of internal friction. In case of necessity of movement of construction equipment on the constructed layer of ash and slag mixture earth bed or at long technological breaks it is recommended to make a layer of sand.
- When constructing ash and slag mixtures earth bed it is obligatory to carry out works on slope reinforcement. Strengthening of slopes prevents the development of erosion processes under the action of water and wind. and also prevents dusting of the earth bed.

According to the results of the performed works an experimental design of the earth bed on the motor road “Siberia” in the Irkutsk region with the use of ash and slag mixtures was built.

The construction of the road section with ash and slag mixtures earth bed has a level of operational condition not lower than the construction of the road section with earth bed from local soils.

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