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STUDY ON THE APPLICATION OF FLY ASH IN ROAD AND AIRPORT CONSTRUCTION

Stepanchuk Oleksandr Vasylovych[1], Yang Shilin[2], Hrabovchak Valentyna Valentynivna[3]
[1]Doctor of Technical Sciences, Professor,
Academician of the Academy of Technical Sciences of Ukraine, Corresponding Member of the Engineering Academy of Ukraine, National Aviation University, Kyiv, Ukraine,
e-mail: oleksandr.stepanchuk@npp.nau.edu.ua, orcid: 0000-0002-2822-3471
[2]National Aviation University, Kyiv, Ukraine,
e-mail: urbeats@icloud.com, orcid: 0000-0001-9599-6960
[3]PhD in Engineering, Deputy Dean of the Faculty of Ground Facilities and Airfields,
National Aviation University, Kyiv, Ukraine,
e-mail: grabovchakvv@gmail.com, orcid: 0000-0002-6315-9639

Abstract. This thesis investigates the use of fly ash obtained from various thermal power plants in China to produce heavy concrete, especially in road and airfield construction. It includes a comprehensive analysis of fly ash samples' chemical and physical properties, their radionuclide content, and their interaction with other materials in the concrete mixture. The study examines how fly ash affects concrete properties such as compatibility, density, frost, and water resistance. Various tests and analyses are presented, including micrographs of fly ash samples, their chemical composition, and physical and mechanical properties. The study also investigated the reaction mechanism of fly ash in hardened concrete and its role in improving the strength and durability of concrete. The conclusions emphasize the beneficial role of fly ash in concrete mixtures, especially in enhancing stability and corrosion resistance.

Purpose. *This study aims to analyze the effect of fly ash on various properties of concrete, such as ease, strength, and durability. It seeks to understand the chemical and physical interactions of fly ash in concrete mixtures, emphasizing improving the overall performance and sustainability of concrete by incorporating fly ash.*

Methodology. *The study utilized modern theoretical, experimental, and physic-chemical research methods (electron microscopy). Experimental studies were conducted under laboratory conditions and on natural objects using modern measuring equipment.*

Results. *The following two results were obtained in this study through theoretical analysis and experimental studies: 1. Incorporation of fly ash into concrete mixtures significantly improves the performance of the concrete, with the main findings including enhanced strength and durability, improved workability, and better resistance to environmental factors such as frost and water; and 2. Fly ash positively affects the physical and mechanical properties of the concrete, making it a functional additive in the production of heavy-duty concrete.*

Scientific novelty. *The scientific novelty of this study can be summarized as follows: 1. It is the first comprehensive study of the use of fly ash from several thermal power plants in China to produce heavy-duty concrete. 2. It further deepens the understanding of the chemical and physical properties of fly ash and its effect*

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on the performance of concrete. 3. This study provides the first detailed description of the reaction mechanism of fly ash in concrete hardening and further deepens the knowledge of utilizing industrial by-products to improve the strength and durability of concrete.

Practical relevance. *The practicality of this research lies in its potential to enhance the construction industry through the sustainable and efficient utilization of fly ash in concrete production. This research supports environmentally friendly construction practices by demonstrating that fly ash can be efficiently utilized in concrete mixtures. It encourages the recycling of industrial by-products, reducing waste and contributing to more sustainable construction methods.*

Key words: *fly ash, slag mixture, fly ash fiber, cement, concrete, fly ash stone, coal combustion products, modified concrete materials, industrial waste, pavement repair, concrete pavement, aerodrome pavement, roads, airfield construction.*

INTRODUCTION

Fly ash (4 samples) from various thermal power plants in China, obtained by electrostatic separation of pulverized particles from the exhaust gases of acceptable ground coal combustion, was used as a component in this work to produce heavy concrete. All samples' fly ash particles have spherical shape and smooth surface texture [19; 11]. Fly ash of the samples contains larger particles with voids in the middle filled with smaller vitrified ash dust particles (Figs. 1, 2).

The content of fly ash radionuclides corresponds to the 1st class of construction materials. The chemical composition of fly ash samples is given in Tables 1–5.

The physical and mechanical properties of fly ash samples are given in Table 2.

Cement M 500 produced by PJSC "Podolsk Cement" was used as a binding material. Physic-chemical characteristics are given in Tables 6–8.

Natural quartz sand DP "Aground" was used as fine aggregate to manufacture concrete mixtures. Sand grain size modulus Mkr. = 2.7. Bulk density 1579 kg/m, actual density = 2.633 kg/m. The sand belongs to the group of course I class. Emptiness is 40%. The content of dust and clay particles is 1.2%. Sand meets the requirements of DSTU B B.2.7-32-95. The granulometric composition of sand is presented in Table 9.

As a coarse aggregate for concrete mixtures, crushed granite fraction 5–20 mm was produced by TOV "Mokryansky quarry". Strength of crushed stone 1200. Frost resistance 300 cycles. Actual density: 2,701 g/cm3. Dust and clay particles content 1.0%. Water absorption is 0.9%. The content of lamellar and needle-shaped grains is 23%. Crushed stone corresponds to DSTU B.2.7-71-98 (GOST 8269.0-97). The grain composition of crushed stone and complete residues on sieves are given in Table 10.

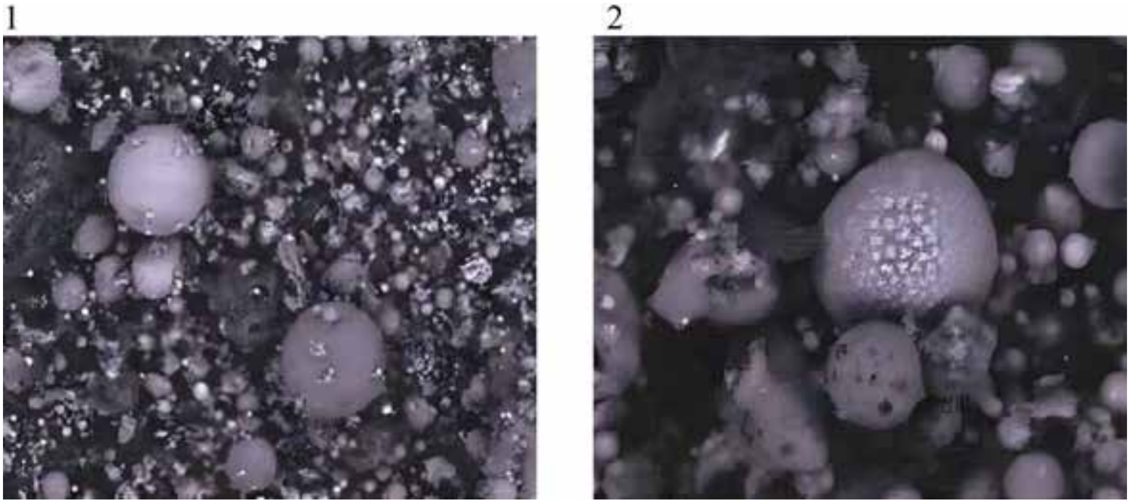

Fig. 1. Micrographs of fly ash samples 1 and 2:
1 – magnification 10000; 2 – magnification 5000

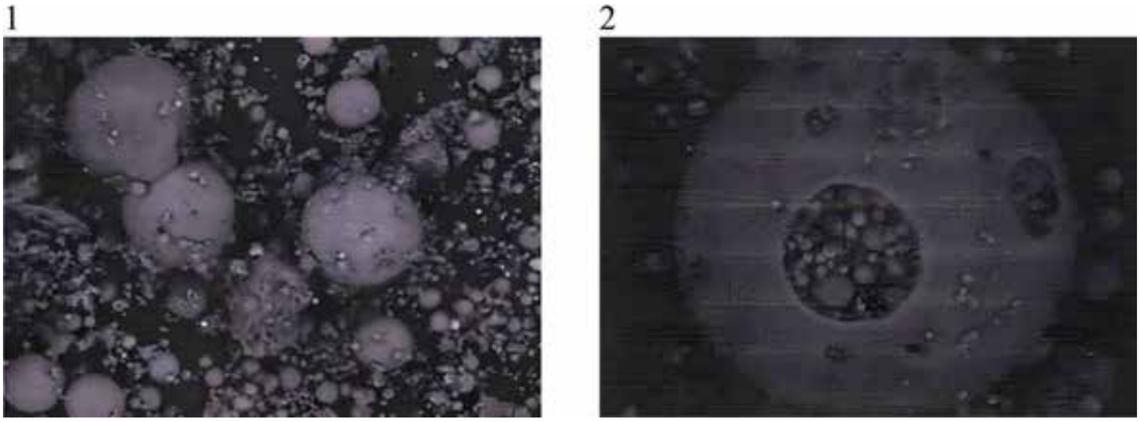

Fig. 2. Micrographs of fly ash samples 3 and 4:
1 – magnification 10000; 2 – magnification 5000

Table 1

Chemical composition of fly ash, % mass %

Elemental content in terms of oxides	Sample number			
	Fly ash № 1	**Fly ash № 2**	**Fly ash № 3**	**Fly ash № 4**
SiO_2	30	48	55	43
Al_2O_3	11	35	19	22
$Fe_2C>3$	9	10	14	14
CaO	42	4	7	1.5
MgO	6	0.7	2.3	2.3
K_2O	1.2	0.7	1.3	1.2
Na_2O	0.8	0.3	1.4	0.8
TiO_2	0	0.8	0.8	0.7

Table 2

Physical and mechanical properties of fly ash samples

Sample number	Bulk density, g/cm^3	Actual density, g/cm^3	Sieve residue 0.071	Uniformity of changes in volume	Specific surface, cm^2/kg
Fly ash № 1	1.216	2.020	13	Unchanged	2840
Fly ash № 2	1.113	1.984	10	Unchanged	2950
Fly ash № 3	0.913	1.871	8	Unchanged	3040
Fly ash № 4	1.119	2.105	9	Unchanged	3025

Table 3

Water requirement and setting time of fly ash

Sample number	Water consumption, Water/Ash	The average density of cement test NDCT, %	Setting time, min	
			start	**end**
Fly ash № 1	0.21	21.00	225	315
Fly ash № 2	0.23	22.50	185	310
Fly ash № 3	0.38	37.50	255	320
Fly ash № 4	0.31	31.25	215	305

ANALYSIS OF PREVIOUS RESEARCH

The conducted studies [8; 12; 17; 20] have shown that fly ash from China (samples No. 1–4) practically does not contain unburned carbonaceous particles, which appear during roasting and are harmful inclusions, as they are not resistant to oxidation, can change volume when moistened, are stress concentrators and reduce the frost resistance of products using fly ash [9; 21]. However, it is necessary to consider that unroasted particles are not residues of initial coal but new coke residues [18; 10], characterized by sufficiently high mechanical strength and high adhesion to cement [7; 13; 22]. Therefore, even their increased amount does not hinder the use of fly ash.

Table 4

Determination of ash and slag mixture moisture content

Sample number	Bins mass, g	Mass of bins with material before drying, g	Mass of bins with material after drying, g	Moisture, % by mass	Average value	Beaker number	SOU Requirements, not more
Fly ash № 1	22.6	73.9	67.2	15.0	14.6	279	15 (group III)
	22.2	68.8	62.6	15.5		327	
	21.7	61.9	57.1	13.3		280	
Fly ash № 2	22.5	57.6	53.9	11.8	10.6	362	15 (group III)
	22.6	65.2	62.5	8.2		279	
	21.6	50.9	47.8	11.8		397	
Fly ash № 3	22.7	65.6	59.5	16.6	15.4	228	15 (group III)
	22.4	71.2	65.1	14.3		276	
	22.5	64.8	59.2	15.2		284	
Fly ash № 4	21.78	81.6	76.7	8.9	9.5	235	15 (group III)
	23.6	77.2	72.0	10.7		389	
	22.3	80.6	75.9	8.8		241	

Note: Moisture content was determined for three samples.

Table 5

Determination of mass loss on frying of fly ash produced in China (samples No. 1–4)

Sample number	Teagle number	Capacity mass, g	Mass of container and material before vaporization, g	Mass of capacity and material after vaporization, g	Loss of mass, %	Average value, %	SOU Require-ments
Fly ash № 1	I	192.8	201.1	200.7	5.1	4.3	5-10
	II	210.5	222.9	222.4	4.3		
	III	222.3	236.6	236.1	3.6		
Fly ash № 2	I	198.5	208.6	208.3	3.1	3.6	5-10
	II	205.4	218.5	217.8	5.6		
	III	212.6	227.7	227.4	2.0		
Fly ash № 3	I	201.8	211.9	211.3	6.3	4.5	5-10
	II	207.2	219.5	219.1	3.4		
	III	203.5	227.4	226.9	3.7		
Fly ash № 4	I	222.2	236.5	236.1	2.8	3.9	5-10
	II	217.5	229.8	229.3	4.0		
	III	218.4	230.7	230.1	4.8		

Note: determining weight loss during frying is carried out on three samples.

Table 6

Mineralogical composition of clinker, mass %

Chemical formula	Mark cement M 500
C_3S	61.4
C_2S	17.0
C_3Al	4.9
C_4AlFe	13.7

Table 7

Chemical composition of cement, mass % (according to manufacturer’s data)

Chemical formula	Mark cement M 500
SO_3	2.84
SiO_2	21.16
Al_2O_3	4.47
Fe_2O_3	4.25
CaO	64.71
MgO	0.85
CaO	–
R_2O/Na_2O	0.34

Table 8

Physical and mechanical characteristics of cement, mass %

Indicators	Mark cement M 500
Average density of cement dough, %	25.50
Setting time, -min, – beginning – end	3–25 4.30
Activity, MPa	54.4
The fineness of grinding by residue on sieve № 008, %	8

Table 9

Granulometric composition of sand

Sieve sizes, mm	Partial residuals		Full balances, %
	g	%	
10	20	1.0	–
5	39	1.95	–
2.5	31	3.1	3.1
1.25	35	3.5	6.6
0.63	90	9.0	15.6
0.315	283	28.3	43.9
0.16	432	43.2	87.1
<0.16	129	12.9	100

Table 10

Grain composition of crushed stone

Sieve sizes, mm	Partial residuals, g	Partial balances, %
20	784	7.84
10	6468	64.68
5	2630	26.30
passed	1.72	1.72

The supposed increase in the time of maintaining the mobility of the concrete mixture and improving its workability [6; 14; 15], as well as a decrease in the water-cement ratio when replacing part of the cement with fly ash, is confirmed by the results of microscopic studies of fly ash. Fly ash particles of all samples have spherical shape and smooth surface texture, ensuring the earlier studies [11; 19].

It is known that fly ash can be used in road and airfield construction both in pure form as an additive to traditional road-building materials and with the addition of cement [1; 2]. As a material for constructing unreinforced layers of road base, fly ash is in a mixture of crushed stone or gravel, whose grain composition meets the requirements of DSTU B B.2.7-30.

Fly ash is used for the foundation of transitional and improved lightweight types of pavements on the roads of IV–V categories, as well as the bottom layers of the base under the improved lightweight and capital pavements on the streets of III category.

However, as practice shows, crushed stone and gravel materials with fly ash and cement addition are more often used for base construction.

The physical and mechanical properties of cement-reinforced mixtures with fly ash should meet the requirements of HBN B.2.3-218-541.

Cement-reinforced fly ash with the addition of stone material shall meet the requirements of GBN B.2.3-37641918-554.

Cement-reinforced milled materials using fly ash shall meet the requirements of HBN B.2.3-218-545.

Cement-reinforced crushed stone or gravel mixtures with the use of fly ash, which meet the requirements of the first group according to HBN B.2.3-218-541 and material grades M20, M40, M60, M75 according to GBN B.2.3-37641918-554, are intended for the arrangement of top layers of bases under improved pavements of capital and lightweight type on roads of I–III category, as well as pavements with protective layers on roads of IV–V categories.

Cement-reinforced crushed stone or gravel mixtures using fly ash, which meet the requirements of the second group according to HBN B.2.3-218-541 and have grades M10, M20, M40 according to HBN B.2.3-37641918-554 and HBN B.2.3-218-545, are intended for the arrangement of lower layers of bases for lightweight and transitional types of pavements on roads of II–III categories, as well as bases for pavements of roads of IV–V categories.

Cement-reinforced crushed stone or gravel mixtures with fly ash of the third strength group according to HBN B.2.3-218-541 and M10, M20 grades according to HBN B.2.3-37641918-554 and HBN B.2.3-218-545 are designed for the bottom layers of bases under the pavements of roads of III–IV categories, as well as for the construction of bases on the streets of V category. Distribution of fly ash into groups is carried out according to SOU 42.1-37641918-104.

Selection of the composition of reinforced fly ash mixes of samples No. 1–4 is carried out experimentally considering the properties of used materials, weather and climatic conditions of construction, intensity of automobile traffic, and purpose of structural layers of road pavement. Determination of the composition of reinforced ash-and-slag mixtures is carried out before choosing such a ratio between the constituent components, which reliably and most economically provides the mixtures of given strength and frost resistance. Recommended grain compositions are shown in Table 11.

To reduce cement consumption, accelerate hardening, and increase frost resistance, it is recommended to add activator additives [3].

The content of needle-like, silty, and clay particles in crushed stone, crushed stone-sand, and gravel-sand mixtures should not exceed 5%, including clay particles – no more than 2%. The frost resistance of crushed stone or gravel used must be not lower than the required frost resistance of the reinforced mixture. The exact requirements should be met by all types of industrial waste used. In addition, the fortified fly ash of stone materials can be carried out by mixing technology in plants or on the road. If appropriate mechanisms are available, the plant mixing technology should be favored (Table 12).

The results of the determination of fly ash samples to the group of ash-and-slag mixtures are given in Table 13.

Fly ash samples 1–4 belong to group III of ash-and-slag mixtures according to SOU 42.1-37641918-104. This group's fly ash can be used to construct and repair highways and airfields. But fly ashes belonging to group II are optimal for the use of their physical and mechanical characteristics. Mixtures of ash and slag mixtures of group III can be used for strengthening with mineral binder – cement or lime for improvement of physical and mechanical properties of coarse clastic (crushed stone mixtures and unbound soils).

Analyzing the data of Table 14, it is evident that in pure form, fly ash of samples No. 1–4 cannot be used for road base construction. In a mixture with cement, fly ash samples No.1–4 can be used as an M10 mixture with the optimum amount of cement of 10–20 % by weight. Thus, fly ash samples No. 1–4 reinforced

Table 11

Requirements for grain composition of mixtures of stone materials, industrial waste, and soils according to HBN B.2.3-37641918-554

Conditional designation of the mixture	Max. grain size, mm	Total residue of mineral grains, in percentage by mass, on a sieve with aperture size mm									
		40	20	10	5	2.5	1.25	0.63	0.315	0.14	0.071
CSM 40	40	0–10	10–40	35–65	50–80	60–85	70–90	75–95	80-97	85-98	87-99
CSM 20	20	–	0–10	20–40	35–65	50–80	60–85	70–90	75-95	80-97	85-98
CSM 10	10	–	–	0–10	25–40	45–65	60-80	70–85	75-90	75-95	85-98
CSM 5	5	–	–	–	0–10	30–40	50–65	65–80	75-85	80-90	95-97
GM 2.5	2.5	–	–	–	–	0–10	30–40	55–65	70-80	80-90	82-92
GM 1.25	1.25	–	–	–	–	–	0–10	35–45	60-70	75-85	82-91
GM0.63	0.63	–	–	–	–	–	–	0–10	60-70	70-80	80-90

Note: CSM – crushed stone mixtures, GM – gravel mixtures

Table 12

Groups of ash-and-slag mixtures

Name of indicators	Groups of ash and slag mixtures		
	I	II	III
Fly ash content, % by mass	<25	25–50	>50
Moisture, % by mass, not more	7	10	15
Mark of ash and slag component on strength	300	200	Not standardized
Mark of ash and slag component on frost resistance	F50	F25	Not standardized

Table 13

Belonging of fly ash samples to specific groups of ash and slag mixtures

Sample number	Indicators		Belonging to the group of ash and slag mixtures according to SOU 42.1-37641918-104
	Fly ash content, % by mass	Humidity, % by mass, no more than	
Fly ash № 1	92.7	4.6	III
Fly ash № 2	92.5	6.6	III
Fly ash № 3	98.2	5.4	III
Fly ash № 4	99.7	3.5	III

Table 14

Physical and mechanical properties of fly ash sample No. 1–4

Sample number	Mix composition		Pavement layer	Data obtained			
	Fly ash, %	Cement, %		Compressive strength in dry state R sit, MPa	Compressive strength in water-saturated condition R sit. in, MPa	Tensile strength at bending R zig, MPa	Coefficient of frost resistance 15 freeze-thaw cycles Kmrz Base
Fly ash № 1	100	0	Ground	Undefined	Undefined	Undefined	0.05
	95	5		0.35	0.25	0.2	0.30
	99	10		0.40	0.25	0.25	0.40
	85	15		0.43	0.30	0.25	0.45
	80	20		0.45	0.35	0.30	0.50
Fly ash № 2	100	0	Ground	Undefined	Undefined	Undefined	0.05
	95	5		0.50	0.30	Undefined	0.50
	99	10		0.9	0.75	0.30	0.55
	85	15		1.2	0.90	0.35	0.55
	80	20		1.3	1.1	0.35	0.60
Fly ash № 3	100	0	Ground	Undefined	Undefined	Undefined	0.1
	95	5		0.8	0.55	0.20	0.6
	99	10		1.1	0.75	0.25	0.60
	85	15		1.3	0.90	0.40	0.65
	80	20		1.4	1.1	0.40	0.65
Fly ash № 4	100	0	Ground	Undefined	Undefined	Undefined	0.1
	95	5		0.50	0.40	0.25	0.50
	99	10		0.90	0.65	0.25	0.65
	85	15		1.1	0.95	0.40	0.60
	80	20		1.4	1.1	0.45	0.65
Requirements of SOU B.2.3-37641918-554				Not normalized	Not less than 1.0 (for M10)	Not less than 0.25 (for M10)	Not normalized

with cement mixture M10–M20 can be used for making the bottom layers of two-layer base on roads of II–III categories and one-layer base on roads of IV–V categories and pavement on roads of V category. On the base made of cement-reinforced fly ash, the overlying layers of road pavement are allowed to be arranged immediately after the strength is sufficient for the passage of technological transport (up to 70% of the standard). Considering the increased intensity and tonnage of freight transport, even on the roads of lower categories, building base layers from fly ash reinforced with cement with the addition of stone material is more appropriate.

Earlier, it was because mainly acidic fly ash was used as a hydraulic admixture in heavy concrete [4]. However, work in recent years has shown that basic fly ash can also be used in concrete mixtures [5]. Because the transferred fly ash samples belong to basic fly ash, it is necessary to determine their participation in the Portland cement curing process [16].

PURPOSE

It is known that such property indicators characterize concretes as workability, average density, porosity, and delamination. The main characteristic of a concrete mixture is its consistency, which is assessed by workability, i.e., the ability of the mix to fill a mold or formwork with the least amount of external energy. The water-cement ratio is the main factor that determines the workability (consistency) of a concrete mixture. The water content depends on the type and quantity of cement, specific surface area of aggregates, fine-to-coarse aggregate ratio, and others. The above factors rely on the process of hardening concrete, that is, reducing or increasing its water requirement and the amount of cement, as well as reducing or increasing the time of demolding of the structure in monolithic concreting and in the production of precast concrete – to determine the time of heat treatment of products. This study aimed to explore and understand the effectiveness of using fly ash from a thermal power plant in China to produce heavy-duty concrete. This includes examining how fly ash enhances concrete's strength and corrosion resistance, thereby improving its overall performance and sustainability. When fly ash is added, the concrete hardening process depends primarily on the interaction of this aggregate with calcium hydroxide, which is formed during this process. Therefore, the effect of fly ash on the hardening process of concrete was studied based on interaction with calcium hydroxide (CaOH2).

RESULTS AND DISCUSSION

The kinetics of calcium hydroxide uptake by fly ash samples was studied in terms of the change in the pH of the medium and the change in calcium hydroxide content in the solution. The study used fly ash samples No. 1–4 (produced in China). The peculiarities of the interaction of fly ash with calcium hydroxide solution, which is formed in hardening concrete, were studied on the same fly ash samples (No. 1–4 produced in China). A sample of mineral admixture of sedimentary origin – opoka was used for comparison. The calcium hydroxide content in the solution in terms of CaO over time is presented in Table 15.

Analyzing the obtained results, we can note the following:

– in a sample of calcium hydroxide solution, in which opoka is present, a decrease in CaO content is immediately observed: after one day by 49%, after three days by 60%, after 7 days by 72%, which is due to the absorption of calcium hydroxide from the solution by opoka;

– unlike classical pozzolanic mineral additives of sedimentary origin (opoka), intensively absorbing calcium hydroxide immediately after contact with the liquid phase, fly ash practically does not absorb calcium hydroxide from the solution for up to 14 days. At the hydration of fly ash at the beginning, there is an increase in the number of calcium ions in the solution, which allows us to note another characteristic of the interaction of fly ash with the liquid phase, different from the classical chemical reaction of the interaction of pozzolanic additive with the liquid medium;

– on the 28th day, fly ash absorbed calcium hydroxide from the solution five times less than opoka.

The reaction mechanism of fly ash in hardening concrete involves two main stages:

– adsorption of liquid phase on the surface of fly ash particles;

– formation of an aqueous intermediate layer between the shell of hydration products and the surface of ash particles at a layer thickness of up to 1.0 μm.

This layer will play a positive role in the concrete hardening process, as it provides the output of calcium ions from the ash, resulting in erosion of the particle surface and formation of depressions where the reaction products with calcium hydroxide are deposited. The strength of concrete may increase due to the formation of bonds between ash particles and cement hydration products. Concrete with fly ash will continue to grow in strength even in more extended curing periods at low reaction rates by the above mechanism. The pH values of the mortars were in the range of 11.6–11.8 and practically did not change for 28 days. After 28 days, the solid phase was filtered. The filtrate did not detect the content of ions Mg^{2+}, Fe^{3+}, $A1^{3+}$, and CO^{2-} Iron and aluminum oxides. The silicon dioxide content was significant in the opoka sample and amounted to 113 mg/l. The silicon oxide content in the

Table 15

CaO content in solution with ash and opoka samples over time

Sample number	CaO content, mg/l					
	Solution of calcium hydroxide Ca (OH)2	Time, days				
		1	3	7	14	28
Opoka	224	115	84	64	50	34
Fly ash № 1	224	252	270	260	240	220
Fly ash № 2	224	290	220	269	269	235
Fly ash № 3	224	250	232	224	215	168
Fly ash № 4	224	250	222	224	210	155

samples with fly ash was within the range of up to 12.5mg/l (Table 16).

For differential thermal analysis, cement stone samples were prepared with a water-cement ratio of 0.26, corresponding to the cement dough's normal density. Cement stone samples with 10% replacement of fly ash were made with a water-solid ratio of 0.25%, with 20% replacement – with a water-solid ratio of 0.24%. The curing of the samples was carried out at temperatures of 20, 30, and 50°C. Temperatures of 20 and 30°C correspond to the main temperatures resulting from heat generation during hardening of road monolithic pavements in transportation construction. When concreting in summer, there is a danger of overheating concrete during the curing process. The maximum temperature for hardening concrete is between 80 and 90°C. If these values are exceeded, the necessary measures must be taken to reduce the temperature inside the concrete during the curing process. In some cases, the temperature of concrete increases more than 40°C, so the curing of some specimens was carried out at 60°C.

The specimens were investigated on the first and 7th days after production. Investigations were carried out with an average sample of fly ash taken in equal amounts from samples 1–4. Two characteristic effects were observed on the obtained thermograms of the control composition after a day:

– the first endothermic effect at temperature 165–180°C is explained by the release of adsorption water on the surface and in the cracks of hydration products;

– the second endothermic effect at temperature 495–520°C relates to water release in the almost complete dehydration of calcium hydroxide, accompanied by destruction and rearrangement of the crystal lattice.

Similar processes occur on thermograms with the replacement of cement with 10% fly ash on the first day on the samples hardened at temperatures of 20, 30, and 40°C. The first endothermic effect is observed at 160–175°C. The second – at temperature 517–525°C. On the samples cured at 60°C, an intermediate effect at 200°C is probably associated with the departure of water from calcium hydrosulfoaluminates.

On thermograms with the replacement of 20% of cement with fly ash on the first day, a decrease in temperature with similar endothermic effects is observed. The first peak on specimens cured at 20, 30, and 40°C occurs at 150–160°C. The second peak occurs at a temperature of 507–520°C. This means that complete dehydration of calcium hydroxide was detected at a higher temperature than in the main composition. The samples cured at 60°C showed an intermediate peak at 195°C. Thermograms at 7 days confirm the difference between the control composition and the compositions with fly ash:

– the first endothermic effect on the control cement samples occurs at 175–185°C;

– the second endothermic effect is observed at temperatures 510–520°C.

On thermograms of samples with replacement of 10% of cement with fly ash at the age of 7 days, hardened at temperatures of 20, 30, and 40°C the first effect is observed at a temperature of 175–185°C, which corresponds to the composition without fly ash.

The evaporation of chemically unbound water occurs at the same temperature. The second peak is shifted at a temperature of 515–535°C. The samples cured at 60°C show an intermediate peak at 220°C. On thermograms of samples replacing 20% of cement with fly ash at the age of 7 days, the first endothermic effect was recorded at the temperature of 140–155°C, which is lower than the temperature of the control composition. This means water evaporation occurs at a lower temperature than the control composition. The second peak associated with the reorganization of the crystal lattice occurs at 520–525°C, which is close to the temperature of the control composition. The thermograms of the cement stone without fly ash and with the replacement of part of the cement are presented in Fig. 3.

Thermo-moisture treatment is a technological operation that includes heating concrete

Table 16

After 28 days of interacting fly ash and opoka samples with calcium hydroxide solution, magnesium oxide, and silicon dioxide content in the liquid phase

Sample number	Content of ions in terms of oxide, mg/l	
	MgO	CaO_2
Opoka	90	113
Fly ash № 1	40	9.5
Fly ash № 2	80	12.5
Fly ash № 3	90	20
Fly ash № 4	105	19.5

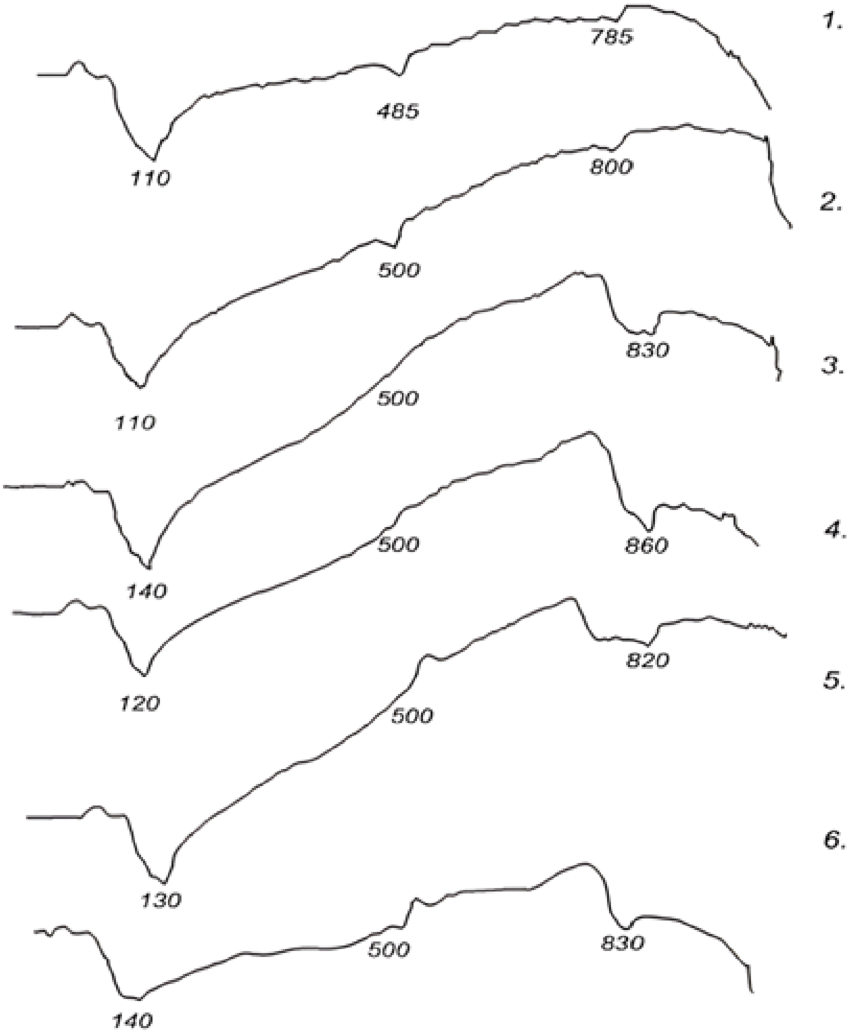

Fig. 3. Thermograms of cement stone without fly ash and with replacement of a part of cement

1 – control composition at the age of 28 days at normal hardening;
2 – control composition at 28 days at thermal-humidification treatment (THT);
3 – composition with ash (B/C=const) at 28 days at normal hardening;
4 – composition with ash (B/C=const) at 28 days at thermal-humidification treatment (THT);
5 – composition with ash with constant plasticity at 28 days at normal hardening;
6 – composition with ash with constant plasticity at 28 days at thermal-humidification treatment (THT).

and reinforced concrete products saturated with steam, because of which their hardening in thermoforms is carried out. There is no direct contact of the product with steam. Assumed quantitative changes in concrete strength with the replacement of part of cement with waste heat and power engineering are confirmed by the results of studies of cement stone with different contents of fly ash. Cement stone samples were prepared from mixtures corresponding to normal density for electron microscopic studies. The samples were hardened under normal humidity conditions (NHC). Cement stone was made from cement without fly ash, with 10% replacement of cement with fly ash, 50% replacement of cement, and fly ash without cement. The investigations were carried out with specimens No. 1 to 4. The test results are presented in Table 17.

The data given in Table 17 shows that the introduction of fly ash leads to a decrease in the water content of cement dough and increases its setting time. Analysis of chipping of cement stone and stone containing fly ash sample No. 1 shows the microstructure development peculiarities depending on the filler percentage. Hydration of clinker phases starts simultaneously on the whole surface of clinker grain contact with water. Water in the process of interaction with cement is saturated with lime, gypsum, and alkalis passing into solution, and as a result, hydrate new formations appear. As shown in Fig. 3.10, the microstructure of cement stone has a fibrous, lamellar form. When 10% fly ash is added to the cement

Table 17

Compositions and test results of cement stone depending on the amount of fly ash

Sample number	Amount of fly ash, % of mass of binder	Water-cement ratio, W/C	Water Demand W/D	Cement batter thickness	Setting time, min	
					Start	End
Fly ash № 1	0	0.26	0.26	25.50	185	235
	10	0.27	0.25	24.50	195	245
	50	0.47	0.23	23.25	205	280
	100	0	0.21	21.00	225	315
Fly ash № 2	10	0.28	0.24	24.20	195	255
	50	0.48	0.23	22.50	210	290
	100	0	0.22	22.00	235	325
Fly ash № 3	10	0.26	0.25	24.50	195	265
	50	0.47	0.22	22.75	215	295
	100	0	0.22	22.00	235	335
Fly ash № 4	10	0.26	0.25	26.25	200	275
	50	0.47	0.24	24.50	205	205
	100	0	0.21	20.00	235	340

dough, the micrograph clearly shows that cement dust balls fill the voids formed by hexagonal plates. When 50% cement is replaced with fly ash, the cement stone structure becomes denser. Micrographs of cement stone with different fly ash contents are shown in Fig. 4.

The dependence of the water-solid ratio on the amount of fly ash (middle sample) introduced to replace part of the cement is presented in Table 18 and Fig 5.

From Table 18 and Fig. 5 it is observed that the introduction of fly ash reduces the water content of the concrete mix. Usually, the water content is in the range of 24–28%. With the increase in the amount of fly ash introduced, the percentage of reduction in water demand increases and is close to linear. An increase in water demand leads to an increase in concrete porosity and a decrease in its performance properties.

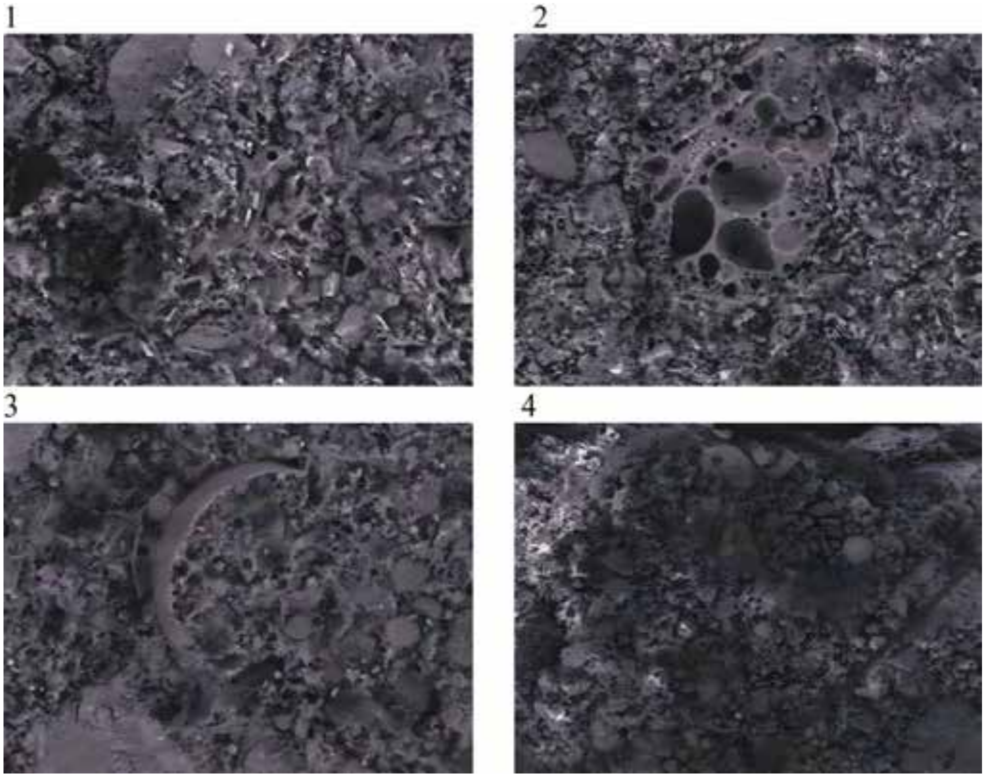

Fig. 4. Micrographs of cement and fly ash stone magnification x 10000

1 – cement + water; 2 – cement + water + 10% fly ash; 3 – cement + water + 50% fly ash; 4 – fly ash + water.

Table 18

Dependence of water-solid ratio on the quantity of fly ash (average sample) substituted for a portion of cement

Quantity of fly ash, %	**0**	**10**	**50**	**100**
W/D	0.26	0.25	0.23	0.21
Reduction of water consumption W, %	0	4.0	13.0	23.8

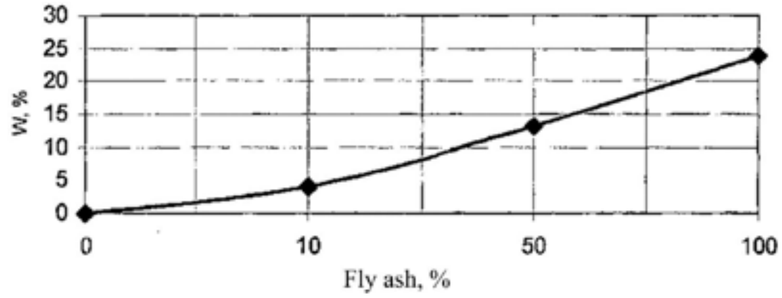

Fig. 5. Effect of fly ash on reduction of water content W of cement stone

CONCLUSION

1. The conducted studies on the model system ash + aqueous solution of calcium hydroxide allowed us to specify the initial period of their interaction, from which it follows that in the initial period of curing, there is no binding of calcium ions, but there release from spherical ash particles. This process helps to explain the effect of ash in the concrete mix on the kinetics of strength growth and other fundamental properties of concrete, such as density, frost resistance, and water resistance.

2. Improvement of concrete properties is due to a stronger association of cement hydration products with ash particles, the surface of which has acquired a relief-shaped surface because of the departure of calcium ions from the surface layers of fly ash, giving it a more active adhesive surface for subsequent interaction with cement hydration products.

3. All ash samples contain in their composition quartz ß-SiC>2 in the amount from 40 to 20% depending on the type of ash; mullite ($3Al_2O_3{\cdot}2SiO_2$) from 5 to 10%; hematite (a-Fe_2O_3) approximately 5–10%; and in addition, some ashes also contain anhydrite ($CaSO_4$) in the amount of roughly 2–4%, periclase (MgO) from 2 to 6%. It should be noted that the ashes, besides the above substances, contain free CaO in the amount of 2–5% and, in some cases, up to 20%, as well as amorphous silicate glass from 10 to 40%.

4. The results obtained and decipherment of the composition of the formed reaction products of ash with liquid phase in concrete allow us to explain the formation of strong bonds between ash particles and cement hydration products. Therefore, concrete containing ash as a component continues to build up strength by the above mechanism.

5. Replacement of 10% cement with fly ash during curing of specimens does not result in a significant difference in endothermic effect temperatures compared to the control composition without fly ash. Replacing 20% cement with fly ash changes the cement stone structure such that the evaporation of adsorption-bound water occurs at a lower temperature. These data were used in planning the experiment and studying the strength of concrete in which the maximum content of fly ash was assumed to be 100%. The optimum amount of introduction of fly ash in the concrete mix is 80%.

6. The positive effect of increased holding temperature on cement compositions with fly ash has been noted, which allows for the reduction of the formation of calcium hydroxide, resulting in increased corrosion resistance of concrete when exposed to aggressive media.

7. Analysis of microscopic studies of cement stone with fly ash allowed us to draw conclusions about the increase of its strength due to a denser structure. Particles of fly ash show pozzolanic properties, binding free lime formed during hardening of Portland cement.

8. The presence of fine particles of fly ash in hardening cement causes acceleration of hydration of clinker minerals because of fine powders, i.e., sliding of new formations.

REFERENCES

[1] Bieliatynskyi, A., Yang, S., Pershakov, V., Shao, M., & Ta, M. (2022). The use of fiber made from fly ash from power plants in China in road and airfield construction. *Construction and Building Materials, 323,*

126537. doi.org/10.1016/j.conbuildmat.2022.126537 [in English].

[2] Bieliatynskyi, A., Yang, S., Pershakov, V., Akmaldinova, O., Krayushkina, K., & Shao, M. (2022). Prospects for the use of ash and slag waste in the construction of Road Pavement. *The Baltic Journal of Road and Bridge Engineering, 17(4)*, 80–94. doi.org/10.7250/bjrbe.2022-17.580 [in English].

[3] Bieliatynskyi, A., Yang, S., Pershakov, V., Shao, M., & Ta, M. (2022a). Study of Carbon Nano-modifier of fly ash in cement concrete mixtures of civil engineering. *Science and Engineering of Composite Materials, 29(1)*, 227–241. doi.org/10.1515/secm-2022-0018 [in English].

[4] Bieliatynskyi, A., Yang, S., Pershakov, V., Shao, M., & Ta, M. (2022b). Study of concrete properties based on crushed stone sand mixture and fiber of fly ash of thermal power plants. *Science and Engineering of Composite Materials, 29(1)*, 412–426. doi.org/10.1515/secm-2022-0167 [in English].

[5] Bieliatynskyi, A., Yang, S., Pershakov, V., Shao, M., & Ta, M. (2022a). Development of building materials based on a high content of fly ash and polycondensation products from Chinese heat and power plants. *Materials Science-Poland, 40(2)*, 270–288. https://doi.org/10.2478/msp-2022-0025 [in English].

[6] Duan, P., Yan, C., & Zhou, W. (2017). Compressive strength and microstructure of fly ash based geopolymer blended with silica fume under thermal cycle. *Cement and Concrete Composites, 78*, 108–119. doi.org/10.1016/j.cemconcomp.2017.01.009 [in English].

[7] Ferreiro, S., Herfort, D., & Damtoft, J.S. (2017). Effect of raw clay type, fineness, water-to-cement ratio and fly ash addition on workability and strength performance of calcined clay – Limestone Portland cements. *Cement and Concrete Research, 101*, 1–12. doi.org/10.1016/j.cemconres.2017.08.003 [in English].

[8] Jia, L., Fan, B., Zheng, X., Qiao, X., Yao, Y., Zhao, R., Guo, J., & Jin, Y. (2020). Mercury emission and adsorption characteristics of fly ash in PC and Cfb boilers. Frontiers in *Energy, 15(1)*, 112–123. doi.org/10.1007/s11708-020-0682-3 [in English].

[9] Jura, J. (2020). Influence of type of biomass burned on the properties of cement mortar containing fly ash. *Construction of Optimized Energy Potential, 9 (1/2020)*, 77–82. doi.org/10.17512/bozpe.2020.1.09 [in English].

[10] Ju, T., Han, S., Meng, F., Lin, L., Li, J., Chen, K., & Jiang, J. (2023). Porous silica synthesis out of coal fly ash with no residue generation and complete silicon separation. *Frontiers of Environmental Science & Engineering, 17(9)*. doi.org/10.1007/s11783-023-1712-2 [in English].

[11] Li, F., Liu, Q., Li, M., & Fang, Y. (2018). Understanding fly-ash formation during fluidized-bed gasification of high-silicon-aluminum coal based on its characteristics. *Energy, 150,* 142–152. doi.org/10.1016/j.energy.2018.02.137 [in English].

[12] Li, D., Liang, Y., Wang, H., Zhou, R., Yan, X., Wang, L., & Zhang, H. (2022). Investigation on the effects of fluid intensification based preconditioning process on the decarburization enhancement of Fly Ash. *Chinese Journal of Chemical Engineering, 44*, 275–283. doi.org/10.1016/j.cjche.2021.03.001 [in English].

[13] Ma, J., Wang, D., Zhao, S., Duan, P., & Yang, S. (2021). Influence of particle morphology of ground fly ash on the fluidity and strength of cement paste. *Materials, 14(2)*, 283. doi.org/10.3390/ma14020283 [in English].

[14] Matsuda, A., Maruyama, I., Meawad, A., Pareek, S., & Araki, Y. (2019). Reaction, phases, and microstructure of fly ash-based alkali-activated materials. *Journal of Advanced Concrete Technology, 17(3)*, 93–101. doi.org/10.3151/jact.17.93 [in English].

[15] Sun, Q., Tian, S., Sun, Q., Li, B., Cai, C., Xia, Y., Wei, X., & Mu, Q. (2019). Preparation and microstructure of fly ash geopolymer paste backfill material. *Journal of Cleaner Production, 225*, 376–390. doi.org/10.1016/j.jclepro.2019.03.310 [in English].

[16] Sri Bhanupratap Rathod, R., Sahoo, P., & Gupta, S. (2023). Application of micro-crystalline cellulose as additive in Portland cement-based and alkali activated slag-fly ash mortar: Comparison of compressive strength, hydration and shrinkage. *Construction and Building Materials, 385*, 131531. doi.org/10.1016/j.conbuildmat.2023.131531 [in English].

[17] Wang, C., Shao, N., Xu, J., Zhang, Z., & Cai, Z. (2020). Pollution emission characteristics, distribution of heavy metals, and particle morphologies in a hazardous waste incinerator processing phenolic waste. *Journal of Hazardous Materials, 388*, 121751. doi.org/10.1016/j.jhazmat.2019.121751 [in English].

[18] Wang, W., Zheng, Z., Feng, C., Gao, X., Qiao, Y., & Xu, M. (2023). Application of zeolite synthesized from coal fly ash via wet milling as a sustainable resource on lead(ii) removal. *Waste Management & Research: The Journal for a Sustainable Circular Economy, 41(7)*, 1246–1254. doi.org/10.1177/0734242x231160077 [in English].

[19] Yang, W., Pudasainee, D., Gupta, R., Li, W., Wang, B., & Sun, L. (2021). An overview of inorganic particulate matter emission from coal/biomass/MSW combustion: Sampling and measurement, formation, distribution, inorganic composition and influencing factors. *Fuel Processing Technology*, *213*, 106657. doi.org/10.1016/j.fuproc.2020.106657 [in English].

[20] Yang, L., Li, D., Zhang, L., Yan, X., Ran, J., Wang, Y., & Zhang, H. (2020). On the utilization of waste fried oil as flotation collector to remove carbon from Coal Fly Ash. *Waste Management, 113*, 62–69. doi.org/10.1016/j.wasman.2020.05.045 [in English].

[21] Yuan, Y., Zhao, R., Li, R., Wang, Y., Cheng, Z., Li, F., & John Ma, Z. (2020). Frost resistance of fiber-reinforced blended slag and class F fly ash-based geopolymer concrete under the coupling effect of freeze – thaw cycling and axial compressive loading. *Construction and Building Materials, 250*, 118831. doi.org/10.1016/j.conbuildmat.2020.118831 [in English].

[22] Zhao, Z., Wang, K., Lange, D. A., Zhou, H., Wang, W., & Zhu, D. (2019). Creep and thermal cracking of ultra-high-volume fly ash mass concrete at early age. *Cement and Concrete Composites, 99*, 191–202. doi.org/10.1016/j.cemconcomp.2019.02.018 [in English].

АНОТАЦІЯ

Степанчук О. В., Ян Шилинь, Грабовчак В. В. Дослідження щодо застосування летючої золи в будівництві доріг та аеропортів.

У цій статті досліджено використання летючої золи, отриманої з різних теплових електростанцій Китаю, у виробництві важкого бетону. Вона включає комплексний аналіз хімічних і фізичних властивостей зразків золи, вмісту в них радіонуклідів та їх взаємодії з іншими матеріалами в бетонній суміші. Дослідження вивчає, як зола-винесення впливає на такі властивості бетону, як сумісність, щільність, морозостійкість і водонепроникність. Представлені різні тести та аналізи, включаючи мікрофотографії зразків золи, їх хімічний склад та фізико-механічні властивості. У дослідженні також вивчено механізм реакції летючої золи у затверділому бетоні та її роль у підвищенні міцності та довговічності бетону. Висновки підкреслюють корисну роль золи-виносу в бетонних сумішах, особливо в підвищенні міцності та корозійної стійкості.

Мета. *Це дослідження має на меті проаналізувати вплив летючої золи на різні властивості бетону, такі як легкість, міцність і довговічність. Воно спрямоване на розуміння хімічної та фізичної взаємодії летючої золи в бетонних сумішах з акцентом на поліпшення загальних експлуатаційних характеристик і стійкості бетону за рахунок включення летючої золи.*

Методологія. *У дослідженні використані сучасні теоретичні, експериментальні та фізико-хімічні методи дослідження (електронна мікроскопія). Експериментальні дослідження проводили в лабораторних умовах та на натурних об'єктах з використанням сучасного вимірювального обладнання.*

Результати. *В результаті теоретичного аналізу та експериментальних досліджень були отримані такі два результати: 1. Включення летючої золи в бетонні суміші значно покращує експлуатаційні характеристики бетону з основними результатами, включаючи підвищену міцність і довговічність, поліпшену оброблюваність і кращу стійкість до впливу факторів навколишнього середовища, таких як мороз і вода. 2. Летюча зола позитивно впливає на фізико-механічні властивості бетону, що робить її корисною добавкою у виробництві надміцних бетонів.*

Наукова новизна. *Наукову новизну цього дослідження можна підсумувати таким чином: 1. Це перше комплексне дослідження використання летючої золи з декількох теплових електростанцій у Китаї для виробництва надміцного бетону. 2. Воно ще більше поглиблює розуміння хімічних і фізичних властивостей летючої золи та її впливу на експлуатаційні характеристики бетону; 3. Це дослідження дає перший детальний опис механізму реакції летючої золи у разі твердіння бетону і ще більше поглиблює знання про використання промислових побічних продуктів для поліпшення міцності і довговічності бетону.*

Практична значущість. *Практична цінність цього дослідження полягає в його потенціалі для розвитку будівельної галузі шляхом сталого та ефективного використання золи-виносу у виробництві бетону. Демонструючи, що зола-винесення може бути ефективно використана в бетонних сумішах, це дослідження підтримує екологічно чисті будівельні практики і заохочує переробку побічних промислових продуктів, зменшуючи кількість відходів і сприяючи більш стійким методам будівництва.*

Ключові слова: *зола-винесення, шлакова суміш, волокно із золи-винесення, цемент, бетон, зольний камінь, продукти спалювання вугілля, модифіковані бетонні матеріали, промислові відходи, ремонт дорожнього покриття, бетонне покриття, аеродромне покриття, дороги, будівництво аеродромів.*

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ВІДОМОСТІ ПРО АВТОРІВ:

Степанчук Олександр Васильович, *доктор технічних наук, професор, академік Академії технічних наук України, член-кореспондент Інженерної академії України, Національний авіаційний університет, Київ, Україна, e-mail: oleksandr.stepanchuk@npp.nau.edu.ua, orcid: 0000-0002-2822-3471*

Ян Шилинь, *кафедра комп'ютерних технологій будівництва та реконструкції аеропортів, Національний авіаційний університет, Київ, Україна, e-mail: urbeats@icloud.com, orcid: 0000-0001-9599-6960*

Грабовчак Валентина Валентинівна*, кандидат технічних наук, заступник декана Факультету наземних споруд і аеродромів, Національний авіаційний університет, Київ, Україна, e-mail: grabovchakvv@gmail.com, orcid: 0000-0002-6315-9639*

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