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CHARACTERISTICS OF FLY ASH AS A COMPOSITE FILLER

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Abstract. The object of the study was composite materials using fly ash from Burshtyn and Kurakhiv TPPs as fillers and polymer dispersions Policril 590 and Latex 2012 as matrices. The relationship between the composition of the types of fly ash from Ukrainian thermal power plants and the peculiarities of the energy state of the dispersed filler particles surface as a factor of interaction with the binder in forming the polymer composite structure was determined. The effect of high concentration of fillers on the formation of the pore structure and indicators of physical and mechanical properties of composites was evaluated. The possibility of adjusting the composite properties in the following range was established: water absorption 4.2–12.7 %, abrasion 0.02–0.06 g/cm^2, residual strain 0.3–1.3, Young's modulus 0.6–49.1 MPa.

Keywords: composite, filler, fly ash, latex, composition, structure, properties.

1. Introduction

The issue of choosing starting materials for the manufacture of composites for various purposes is the subject of numerous studies[1–3]. At the same time, attention is drawn to the possibility of using by-products and waste from various industries as fillers[4, 5].

Ash slag and fly ash occupy a significant place among multi-tonnage thermal energy waste. Ashes and slag are formed in the furnaces of boilers of thermal power plants. The temperature regime and the type of coal (brand and methods of burning it) determine the quantitative ratio between the formed fly ash and slag. Small solid particles that carry flue gases are captured and cleaned by electrostatic precipitators, forming fly ash. Solid particles that settle after burning coal in boiler furnaces give slag. Fly ash and slag are removed hydraulically, separately or jointly[6].

Ash from thermal power plants is used in various industries, including solar energy, heat pumps, heating and cooling systems, industrial processes, and others. It allows effective management of heat loads, reduction of energy costs, and an increase in the stability of heat supply.

Coal combustion at thermal power plants in Ukraine produces 7–9 million tons of ash and slag annually (50–200 g of ash per 1 kWh of electricity produced)[7]. About 40 million tons of ash have been accumulated at the Burshtynska TPP dumps alone[8]. However, according to 2013 data, the share of ash recycling in Ukraine is within 10 %, while in the UK it is 60 %, in France – 72 %, and in Finland – 84 %[9].

More than 80 % of the mineral composition of coal turns into ash, and up to 20 % into slag.

The quality of slag depends on the system of its selection and removal (hydraulic-granulated slag or dry slag is produced). Most state-owned TPPs have a hydraulic slag removal system. Out of the six types of power plants in the Donetsk region, only Kurakhivska has a dry ash removal system[10].

The basis of the fly ash and slag waste classification by chemical composition is the content and ratio of SiO_2, Al_2O_3, Fe_2O_3, CaO, and MgO oxides. The class of ash is determined by the modulus of basicity. If the total content of fly ash is more than 70 % of SiO_2, Al_2O_3, and Fe_2O_3 oxides, it is considered acidic. If the amount of the specified oxides is in the range from 50 % to 70 %, it is the main one. Acidic ashes exhibit pozzolanic properties, the main of which are hydraulic properties.

The chemical composition of ash in the process of burning different brands of solid fuel varies within fairly wide limits[11].

The shape and phase state of ash particles in thermal power plants depend on the mineral composition of coal and its burning temperature. Acid ash particles are usually spherical, and basic ash particles can have an irregular shape[12].

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The problems of studying the composition, physico-chemical properties of ash microspheres, and their use as fillers were studied by several scientists, in particular M. I. Kholdaeva[13], and Ehab Mohamed Hossna Ragab[14].

Nagaraja *et al.*[15] investigated the use of fly ash as a filler for epoxy-based composites with a small amount of it (6–9 wt. %) as an additive to the main filler. However, it was found that the addition of up to 6 wt. % of ash fly significantly improves tensile strength (by 65.3 %) and bending strength (by 31.9 %). And with the addition of 9 % of ash, the maximum improvement in impact strength is achieved (by 74.18 %). In addition, the water resistance of the composite is increased and a uniform distribution of fillers is ensured, as well as the morphological and physical properties of the composite are improved.

Kovalskyi and Sidlak[16] considered progressive Ukrainian technologies for the disposal of ash residues.

However, the main characteristics of ash microspheres given in the literature describe mainly their density, strength parameters, and melting point, which is not sufficient to evaluate them as a filler for polymer composite materials (PCM).

The analysis of literary sources on the properties of fillers of composite materials proved the possibility of using ash microspheres as part of building materials to increase their thermal insulation and operational properties. In addition, the use of industrial waste, such as fly ash, as fillers for polymer composites is becoming increasingly relevant in the context of environmental sustainability. The prospects of using fly ash to improve the mechanical and thermal properties of composites were examined by Nagaraja *et al.*[17].

At the same time, the fields of application are limited due to the lack of information about the surface properties of ash microspheres, and the processes of ash interaction with polymer matrices are still not well understood[18].

Therefore, the study of their structure and surface properties is one of the priority tasks, which determines the expediency and possibilities of their use as a filler for PCM. From the given data, it is clear that the possibility and effectiveness of using fly ash as a component of PCM will depend on the features of genesis, composition, and properties, which became the subject of research in the presented work.

2. Experimental

2.1. Materials

Composite materials based on copolymer-filler systems became the object of research. Ash microspheres from Burshtynska (Ash B) and Kurakhivska TPP (Ash K) (Ukraine) were chosen as fillers. At the Kurakhivska TPP, coal from the Donetsk basin (anthracite) was burned, and at the Burshtynska TPP, coal from the Lviv – Volyn coal basins (coal), *i. e.*, solid fuel has a different mineral composition. Ash also differs in the method of removal: fly ash from the KurakhivskaTPP – dry collection, and ash from the Burshtynska TPP – wet collection.

Aqueous dispersions of Latex 2012 copolymer and polymer Policril 590 (Table 1) were used as binders (matrix).

Aqueous polymer dispersions were chosen due to the need to achieve a high degree of homogenization – uniform distribution in the matrix between filler particles at their increased concentration.

2.2. Research methods

The mineralogical composition of ash microspheres and the quantitative ratio between phases were determined by X-ray structural analysis using a DRON-3M diffractometer (CuK_α radiation, voltage 40 kV, current 20 mA, speed 2 degrees/min)[19]. The surface of the samples was examined using a scanning electron microscope JSM. IR spectra in the range of 4000–400 cm^{-1} were recorded on a Specord IR-75 spectrophotometer (manufactured by Carl Zeiss, Germany).

Table 1. Characteristics of binders

Characteristics	Indexes	
	Latex 2012	Policril 590
Chemical composition	Styrene-butadiene	Acrylic
Styrene content, %	30	–
Physical condition	Aqueous dispersion of white color	Aqueous dispersion of white color
Dry residue content, %	51.0	53.5–55.0
Particle size, nm	140	200
Viscosity, MPa·s	200	□1000
pH	5.5	5.5–7.5
Temperature (MTPU), °C	< 5	0

Determination of the specific surface was carried out by several methods: with the help of a T-3 type pneumatic surface meter (PSK), the essence of the method is to determine the volume of air that seeps through a layer of material during rarefaction; by the BET method, which is based on the adsorption of nitrogen vapor at a temperature of –195 °C by a molecular layer on the surface of the experimental powder[20]; and the Deryagin method, by wetting with liquids[21]. This method consists of establishing the height of the capillary rise of liquid in a cylindrical capillary over a certain time. Using these values, as well as the volume of liquid absorbed by the sample, the specific surface area of the dispersed material is calculated indirectly through the value of the capillary size between the particles. The method uses water as a polar liquid and benzene as a non-polar one, which makes it possible to obtain a specific surface when the adsorbent is in contact with both polar and non-polar liquids. An important condition is the insolubility of the test sample in the liquids used for the experiment.

The granulometric composition was determined by the sieving method. The marginal wetting angle was calculated based on the Washburn equation[22], the porosity and lyophilicity coefficient were determined using water and benzene by the Deryagin method[21]. The energy state of the surface of ash particles was studied by measuring the wetting angle using water and benzene as polar and non-polar liquids, and calculated according to the Owens-Wendt method[23].

The abrasive resistance of samples was determined following DSTU B.V.2.7-212:2009 on a Boehme-type abrasion circle, and mechanical properties "deformation-loading" diagrams under uniaxial compression were studied at room temperature using the automated arrangement that consists of IMAIII-20-78, an analog-digital converter (ADC), a personal computer (PC), and connecting cables. The measurements were performed in a vacuum of 10^{-5} Torr[24].

The technology of manufacturing a composite based on the copolymer-filler system consists of the following operations:

– mechanical activation of filler and binder in a ball mill (20 minutes);

– formation of blanks (according to the volume of the mold) and their maturation (48 hours at room temperature);

– heat treatment of blanks (gradual increase in temperature and exposure for 1 hour at 80 °C);

– cold pressing (5 MPa) of cylindrical samples with a diameter of 10 mm.

3. Results and Discussion

3.1. Properties of fly ash

The filler nature plays an important role in creating polymer composite materials. Therefore, the primary task was to comprehensively investigate the properties of ash microspheres. According to the chemical composition (Table 2), both ashes belong to the acid ones. However, there are some differences: the fly ash sample from the Kurakhivska TPP differs from the Burshtynska TPP sample in the content and quantitative ratio of SiO_2:Al_2O_3 oxides (3.2–2.6), a higher content of alkaline earth and alkaline oxides (13.5–7.6 %) with a significantly lower amount of iron oxides (14.2 against 22.2 %).

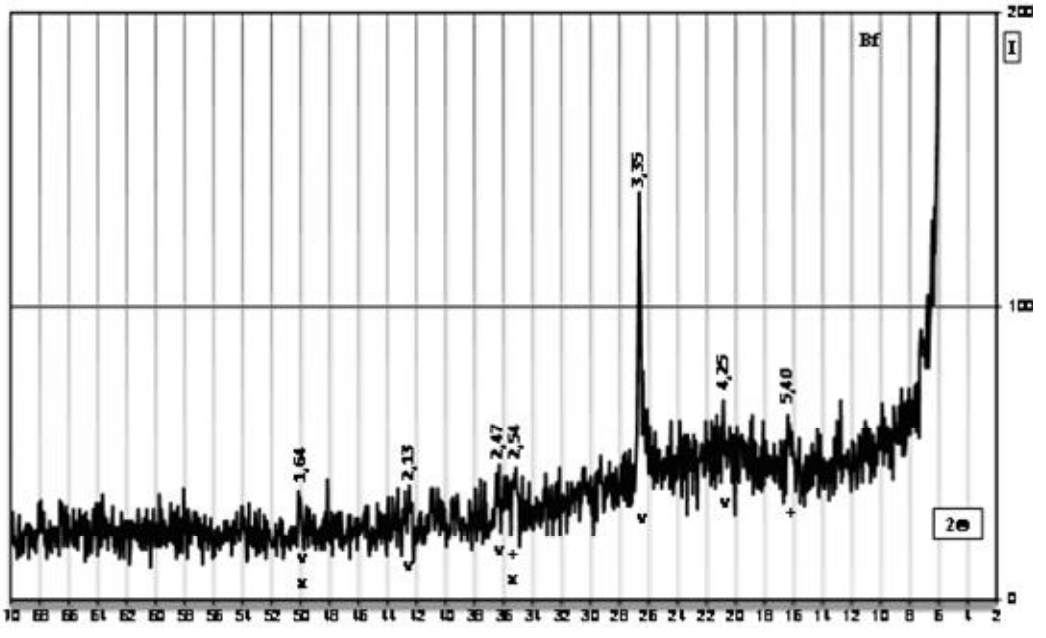


Fig. 1. X-ray diffraction of ash sample from Burshtynska TPP: *v*-quartz, +-mullite, *x*-hematite

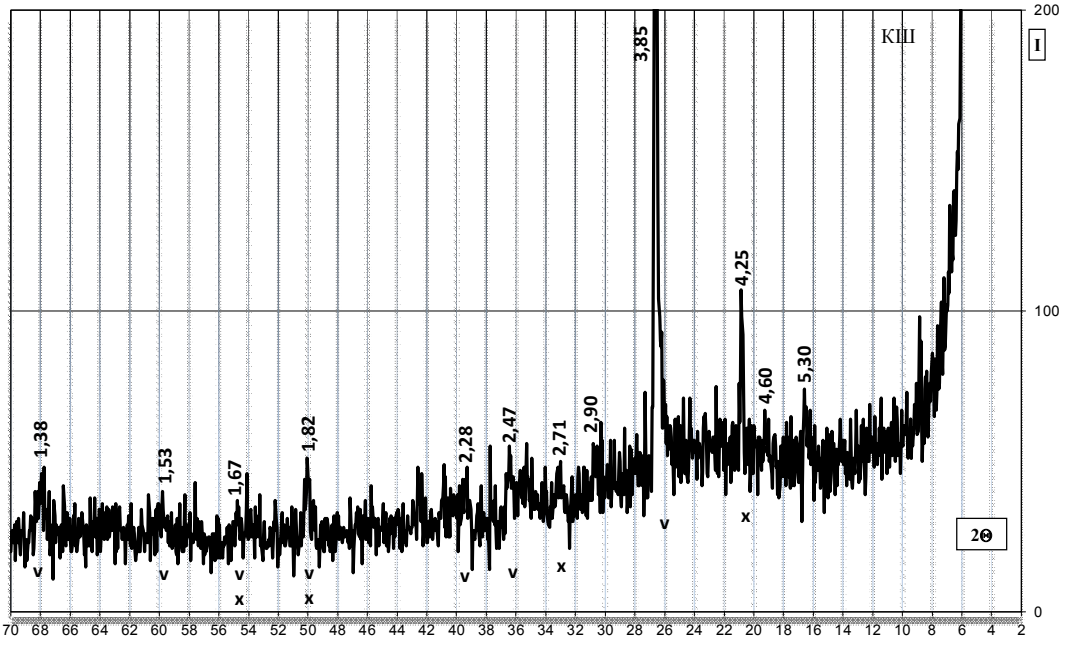


Fig. 2. X-ray diffraction of ash sample from KurakhivskaTPP: *v*-quartz, *x*-hematite

Table 2. Chemical composition of raw materials

Fly ash sample	Oxide content, wt. %								
	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	SO_3	K_2O	v.p.p.
Burshtynska	46.12	18.00	22.17	1.78	4.03	1.46	0.21	2.10	1.49
Kurakhivska	51.53	15.98	14.23	1.67	8.15	1.53	0.76	3.81	0.01

Analysis of the mineralogical composition of the studied raw materials showed that the fly ash sample from the Burshtynska TPP is characterized by the presence of a glass phase and crystalline phases of quartz, hematite, and mullite, while the sample from KurakhivskaTPP is characterized by the presence of a glass phase and crystalline phases of quartz and hematite (Figs. 1, 2).

An important characteristic of ashes that determines their use as a filler is the size of the particles and the percentage ratio of their fractions – granulometric composition (Fig. 3).

It was found that the fraction with a particle size of less than 63 μm has the highest content among the studied ash samples. The content is 75.5 and 48.7 wt. % for Burshtynska and Kurakhivska ash, respectively. The content of the 63–100 μm fraction decreases and amounts to 20 and 25.6 wt. %, respectively. The content of larger fractions for Burshtynska ash does not exceed 2 wt. %. It should be noted that the dispersion of the Kurakhivska ash is somewhat higher, the content of larger fractions does not exceed 8 wt. %, while the content of the largest fraction (>630 μm) reaches almost 4 wt. %.

Particles of ash, which are formed in the flame during coal combustion, are crystallized glass balls (Fig. 4). Studies using electron microscopy have shown that ash microspheres have a shape close to spherical and smooth outer surfaces.

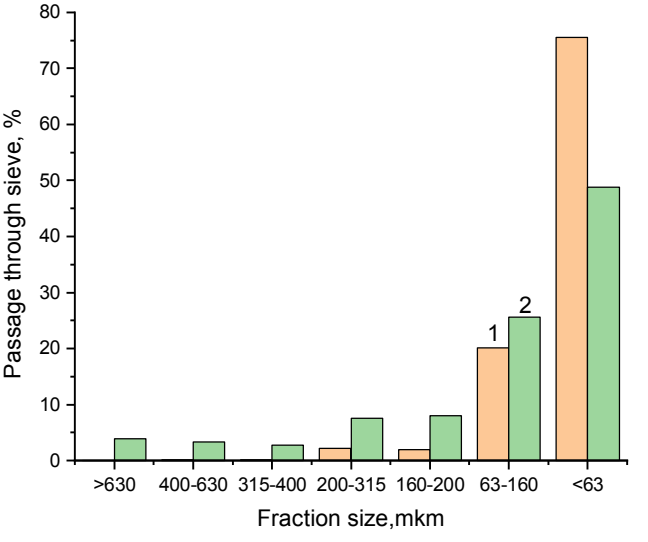
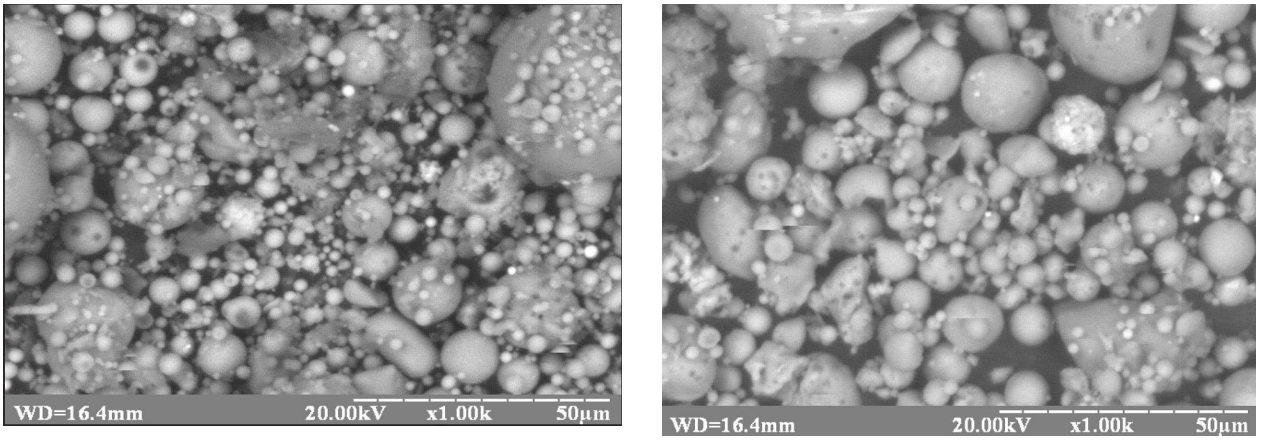
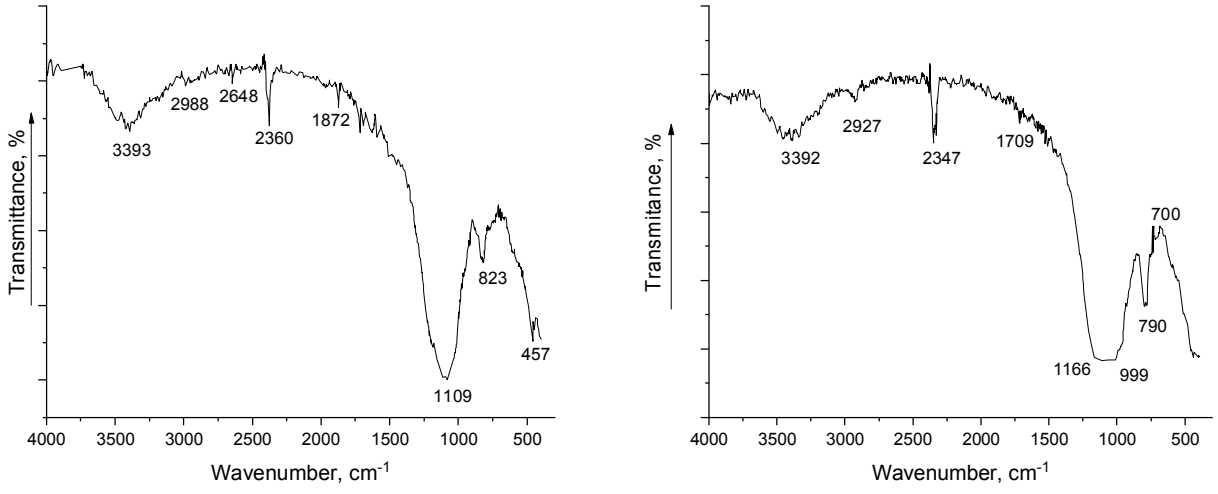


Fig. 3. Distribution of particles by fractions of ash samples from Kurakhivska (1) and Burshtynska (2) TPPs



a b

Fig. 4. Microstructure of ash microspheres: a – Burshtynska; b – Kurakhivska



a b

Fig. 5. IR spectra of ash samples from Burshtynska (a) and Kurakhivska (b) TPPs

Table 3. Lyophilicity and energy state of the fly ash surface

Material	Surface area, m^2/g				Total pore volume, cm^3/g	Average pore diameter nm	Coefficient of lyophilicity	Coefficient of wetting during inflow		Wetting angle, degrees	Surface energy, mJ/m^2
	BET	PSK	According to Deryagin								
			water	benzene				water	benzene		
Fly Ash K	0.68	2.58	3.58	4.69	0.001	2.934	0.64	0.24	0.69	79	39.58
Fly Ash B	3.45	10.07	5.99	11.10	0.002	2.459	0.19	0.13	0.53	69	51.67

The analysis of the chemical composition of the above-mentioned ash microspheres shows that their properties are similar, but certain differences in the mineralogical composition are present. That is why, for a more detailed characterization of the chemical composition of the ashes under study, they were examined by IR spectroscopy (Fig. 5).

There are no significant differences between the spectra of the studied samples. In the range of 3400–3300 cm^{-1} there is an absorption band of the H_2O molecule. The presence of C-H bonds was recorded (absorption bands at 2923–2990 cm^{-1}). Oscillations of carbon (IV) oxide (impurity from the atmosphere) are observed at 2360–2325 cm^{-1}.[25]

In the range of 1170–1000 cm^{-1} there is a broad absorption band corresponding to valence vibrations of the Si-O-Si bond in quartz crystallites[26]. The contour of this band also overlaps individual bands caused by asymmetric vibrations of atoms connected by bonds Si-O-Al, Al-O-Al. Deformation vibrations of SiO_4 tetrahedra in microcrystallites and glassy matrix are manifested by a band of 420–457 cm^{-1}. In crystalline modifications of SiO_2 (coesite, quartz, cristobalite, tridymite), these fluctuations are recorded in the range[27, 28] of 450–500 cm^{-1}.

The bands at 1709 cm^{-1} and 1872 cm^{-1} are characteristic of the vibrations of carbon atoms in the hexagonal cycles of graphene bridges[29].

The bands at 823 cm^{-1}, 790 cm^{-1} are also recorded, which are characteristic of the α-FeOOH lattice and belong to the vibrational oscillations of the Fe-O bonds in the goethite structure. This gives grounds for asserting that the majority of silicates in the structure of ash microspheres are represented by ring silicates of the corresponding structure[30].

To establish the feasibility of using ash microspheres as a filler for PCM, their wettability with polar (water) and non-polar liquids (benzene) was determined. The results of the study are shown in Table 3.

The energy state of the filler particle surface relative to the liquid wetting angle was analyzed accordingly to the Dupré – Young equation[31]. It was established that ash microspheres are much better wetted by non-polar liquids (benzene) than by polar liquids (water). What's more, the studied material is poorly wetted. The wetting angle at the point of contact of the three phases, determined in accordance with the methodology[23], is 69 and 79º for Burshtynska and Kurakhivska ash, respectively. Ash microspheres obtained by burning Kurakhivska coal are characterized by slightly higher wettability both by water and by benzene (0.24 by water and 0.69 by benzene), compared to the ash from Burshtynskaya TPP (0.13 by water and 0.53 by benzene). The coefficient of lyophilicity for ash microspheres obtained during the burning of Kurakhivskaya TPP coal is 0.64, which is higher than for ash microspheres of Burshtynskaya TPP (0.19). Since the contact angle is an indicator of how well a liquid spreads on a surface, and the wettability coefficient indicates the rate of liquid spreading on contact, the contradiction between the contact angle and the wettability coefficient for ashes can be explained by the complex interplay between surface energy, chemical composition and structure material that can affect the wettability and dynamics of the liquid on the surface.

In addition to wettability, an equally important characteristic when studying the properties of powdered materials is their specific surface area. The specific surface of the dispersed phase determines the nature of its interaction with the matrix and depends on the contact surface and the distribution of particles in the dispersion medium. Ash microspheres have a relatively low specific surface area (Table 3). This is directly related to their granulometric composition and their mineral-phase composition. Thus, the specific surface area determined by various methods is greater for Burshtynska ash compared to Kurakhivska TPP ash and is, respectively: when using the BET method – 3.45 *versus* 0.68 m^2/g; by the PSK method, this indicator is equal to – 10.07 against 2.58 m^2/g; when moistened with water – 5.99 against 3.58; with benzene – 11.10 *versus* 4.69 m^2/g.

3.2. Interaction in the polymer matrix – fly ash system

When investigating the interaction between the filler and the binder using IR spectroscopy (Fig. 6, *a*, curve 1), it was established that the acrylic dispersion of Policril 590 is characterized by an absorption band at 1670 cm^{-1}, which corresponds to the monomer units of acrylate[32] and is a result of asymmetric and symmetric valence vibrations of C=O in the carboxyl group. The absorption band at 1435 cm^{-1} corresponds to the vibrational oscillations of the C=C bond, and the presence of a CH bond is indicated by the absorption band at 1100 cm^{-1}.[33] As for the Policril 590 + Fly Ash B system (curve 3), the course of the curve corresponds more to the absorption curve characteristic of the Burshtynska ash but there are certain nuances: in particular, a slight absorption band appeared at 2250 cm^{-1}, which corresponds to the C=C and at 1720 cm^{-1} is characteristic of the C=O bond of the polymer.

The same regularities are observed when Kurakhivska ash was studied (Fig. 6, *c*, curve 3).

Regarding the IR spectrum of the styrene-butadiene dispersion Latex 2012 (Fig. 6, *b*, curve 1), the absorption band at 2980 cm^{-1} is responsible for the CH- connection in the aromatic ring, and the absorption band at 1525 cm^{-1} is directly responsible for the presence of the ring itself. The absorption band at 2852 cm^{-1} confirms the presence of a CH_2 group, and a band at 1500 cm^{-1} indicates the presence of a styrene double bond[34].

For the composite material based on the Latex 2012 + Fly Ash B system (Fig. 6, *b*, curve 3), there is a decrease in the peak intensity at 2980 cm^{-1} with its shift to 2910 cm^{-1}, and disappearance at 1720 cm^{-1}. This confirms that the introduction of filler to Latex 2012 is accompanied by intermolecular interaction. Similar processes are observed when using Kurakhivska ash (Fig. 6, *d*, curve 3).

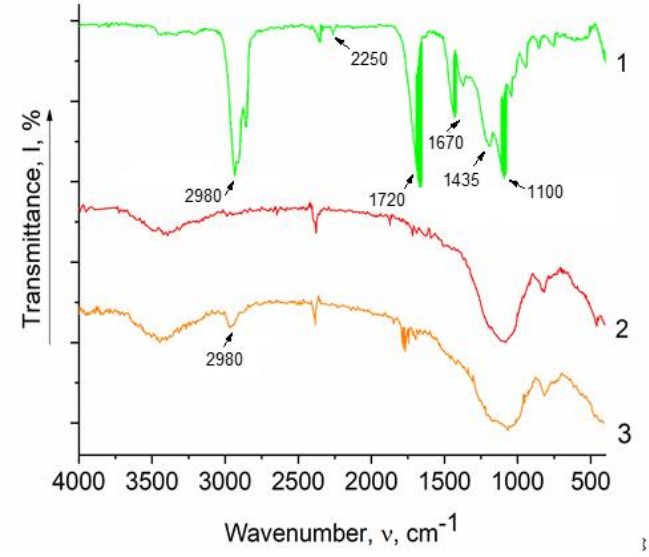


Fig. 6a. IR spectra of samples: 1 – Policril 590; 2 – Fly Ash B; 3 – Policril 590 + Fly Ash B

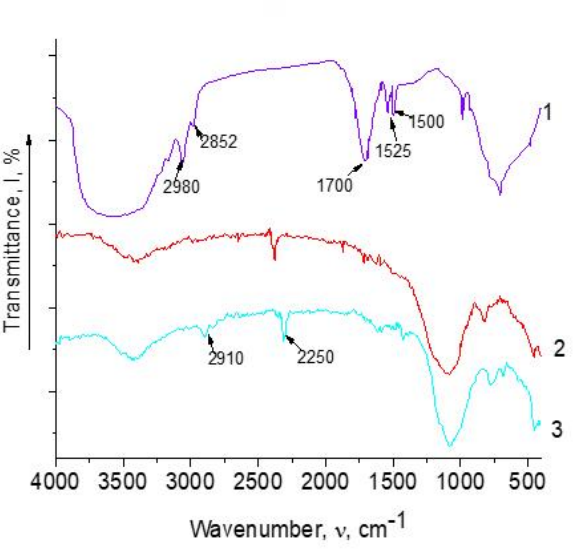


Fig. 6b. IR spectra of samples: 1 – Latex 2012; 2 – Fly Ash B; 3 – Latex 2012 + Fly Ash B

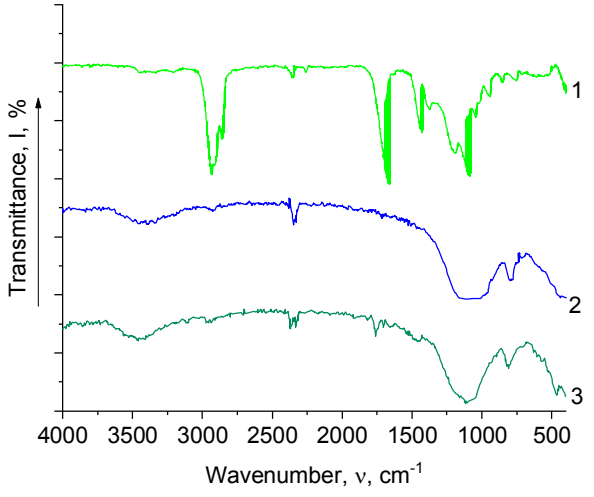


Fig. 6c. IR spectra of samples: 1 – Policril 590; 2 – Fly Ash K; 3 – Policril 590 + Fly Ash K

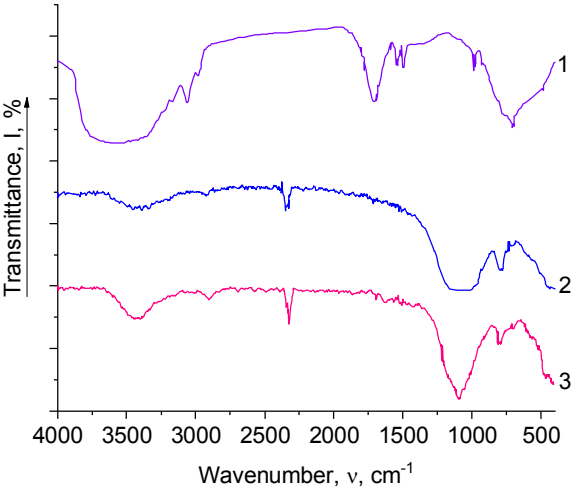


Fig. 6d. IR spectra of samples: 1 – Latex 2012; 2 – Fly Ash K; 3 – Latex 2012 + Fly Ash K

3.3. Determination of physical and mechanical properties of composites

Samples of the composite material were obtained on the basis of binary systems of the investigated fly ash as fillers with binding (Table 4). At the same time, the concentration of fillers with a particle size ≤ 1 mm varied from 65 to 90 wt. %, and the concentration of binders – from 35 to 10 wt. %, respectively.

The indicators of the physical and mechanical properties of composites significantly depend on the type and concentration of the filler. When using both fly ashes with an increase in their concentration, an increase in water absorption and average density is observed. At the same time, the degree of change of these indicators in the specified range of filler concentrations is significantly different. Thus, when comparing composites based on acrylic dispersion (Policril 590) with the use of different lead ash, it should be noted that water absorption when using Burshtynska ash, with an increase in its concentration, varies in the range of 4.2–10.3 wt. %, which is somewhat lower in comparison with composites using Kurakhivska ash (6.3–11.2 %). When replacing the binder with Latex 2012, this trend is observed, but the

values slightly increase. So, for Burshtynska ash, they range from 7.2–10.9 wt. % against 8.3–12.7 wt. % for Kurakhivska ash.

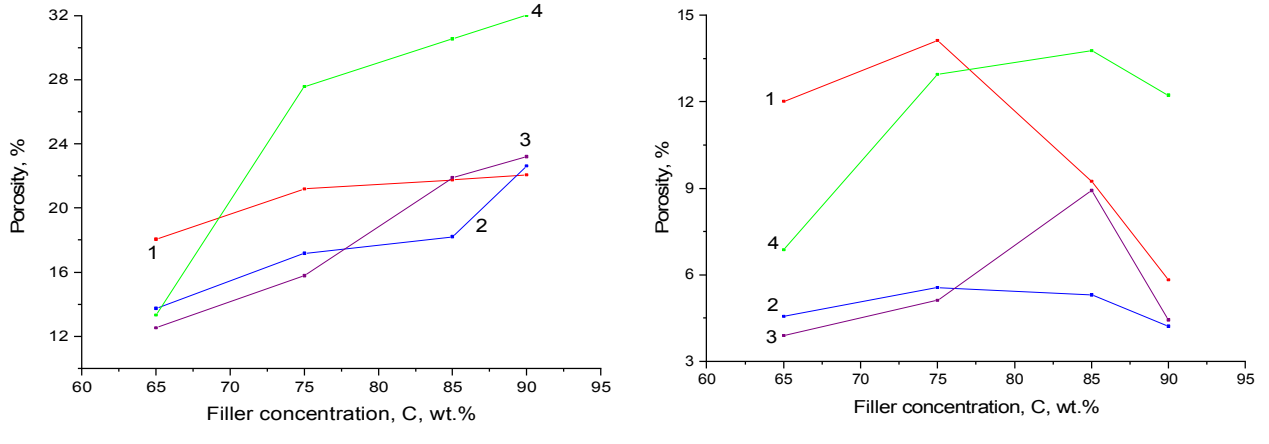
The analysis of the sample structures showed (Table 4) that there is a linear dependence of the porosity increase on the filler concentration.

When comparing composites based on dispersion Policril 590 it should be noted that when applied Burshtynska ash with increasing concentration, the open porosity varies in the range of 6.03–16.23 %, which is somewhat lower compared to composites with Kurakhivska ash (8.62–18.75 %). When the binder was replaced with Latex 2012, this trend continued, but the values increased slightly: 9.17–18.40 % for Burshtynska ash *versus* 10.77–19.79 % for Kurakhivska.

For composites using Burshtynska ash, when replacing the binder with Policril 590 by Latex 2012, the initial value of total porosity decreased by 18.04–22.06 % *versus* 13.74–22.62 %. When using Kurakhivska ash and replacing binder with Policril 590 by Latex 2012, the value of total porosity increased from 12.52–23.19 to 16.92–32.01 % (Fig. 7).

Table 4. The composition and properties of the composite material

Composition of the composite	Concentration of filler, *C*, wt. %	Indexes				
		Water absorption after 24 hours, %	Open porosity, %	Total porosity, %	Average density, g/cm^3	Abrasion, g/cm^2
Policril 590 + Fly Ash B	65	4.2	6.03	18.04	1.44	0.019
	75	4.6	7.07	21.19	1.54	0.019
	85	7.8	12.50	21.74	1.56	0.012
	90	10.3	16.23	22.06	1.57	0.013
Latex 2012 + Fly Ash B	65	7.2	9.17	13.74	1.28	0.094
	75	7.3	11.61	17.17	1.52	0.031
	85	8.5	12.90	18.21	1.59	0.021
	90	10.9	18.40	22.62	1.68	0.057
Policril 590 + Fly Ash K	65	6.3	8.62	12.52	1.33	0.023
	75	7.9	10.67	15.79	1.35	0.026
	85	8.2	12.98	21.90	1.59	0.015
	90	11.2	18.75	23.19	1.68	0.021
Latex 2012 + Fly Ash K	65	4.7	6.45	13.32	1.36	0.045
	75	9.6	14.62	27.57	1.53	0.042
	85	10.8	16.77	30.54	1.55	0.039
	90	12.7	19.79	32.01	1.56	0.071



a b

Fig. 7. Total (a) and closed (b) porosity of the composites depending on the concentration for the experimental systems:

1 – Policril 590 + Fly Ash B; 2 – Latex 2012 + Fly Ash B; 3 – Policril 590 + Fly Ash K; 4 – Latex 2012 + Fly Ash K

As for the closed porosity, its linear dependence on concentration is limited to certain values of the latter, from 75 to 85 wt. %. The porosity of composites plays an important role in the formation of their physical and mechanical properties. With increasing porosity, mechanical resistance decreases and water absorption increases, which was confirmed by our experiments, which are consistent with known works[26].

The obtained results of testing the elastic and strength characteristics of the experimental composites are confirmed by the "loading-unloading" diagrams (Figs. 8–11) with the determination of the characteristics of elastic and plastic deformations, and the effective value of Young's modulus (Tables 5, 6).

All samples have a rather large total deformation $\varepsilon_{pl} \approx 0.30$, which is observed at various values of mechanical load P, depending on the fly ash content and the type of polymer binder. Table 5 displays data on relative deformation ε_{total}, plastic deformation ε_{pl}, elastic deformation ε_{el}, and Young's modulus E for CM system Polymer binder + Fly Ash B with various ash contents. The relations between deformations and Young's modulus E are the following: $\varepsilon_{total} = \Delta l/l_0 = \varepsilon_{pl+}\varepsilon_{el}$, $e = P/\varepsilon_{el}$, where l_0 is the initial thickness of the sample, Δl is the decrease of sample thickness under compression up to loading P. As can be seen from Figs. 8, 9 and Table 5, CM samples with Policril 590 binder are more flexible compared to CM samples with Latex 2012, *i. e.*, the large deformations of samples ($\varepsilon_{total} = 0.30$) occurr at low loading values (0.4–2.0 MPa) and Young's modulus E varies within the range of 1.6–10.2 MPa depending on content of fly ash B. Latex 2012 + Fly Ash B samples are characterized by much higher values of Young's modulus, which range from 29.3 to 60.6 MPa and for the same values of deformation ($\varepsilon_{total} = 0.30$) the higher compression loads (4.4–11.5 MPa) are required. For both Policril 590 + Fly Ash B and Latex 2012 + Fly Ash B CM system Young's modulus E increases with fly ash content, though this dependence is non-monotonic. The obtained results show a clear correlation between an increase in the Young's modulus and a decrease in the deformation of composites. The possible reason is the increased density of bonds in the polymer matrix with an increase in the ash content[35].

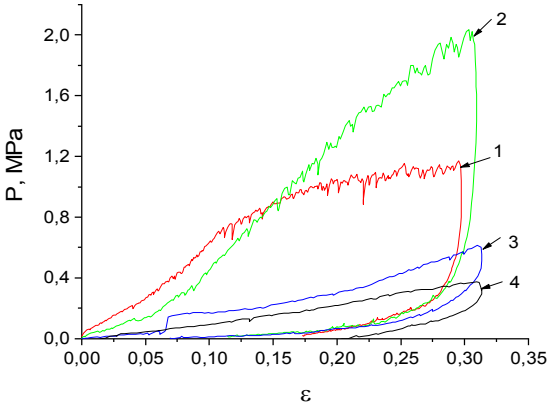


Fig. 8. Dependence of deformation on load for CM system Policril 590 + Fly Ash B: 1 – 90 wt. % of ash; 2 – 85 wt. % of ash; 3 – 75 wt. % of ash; 4 – 65 wt. % of ash

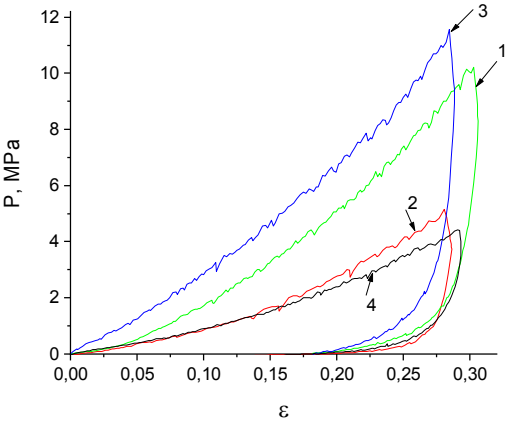


Fig. 9. Dependence of deformation on load for CM system Latex 2012 + Fly Ash B: 1 – 90 wt. % of ash; 2 – 85 wt. % of ash; 3 – 75 wt. % of ash; 4 – 65 wt. % of ash

Table 5. Strength and elastic characteristics of samples using ash from the Burshtynska TPP

Content of Fly Ash B, wt. %	Maximum load, P, MPa	ε_{total}	ε_{pl}	ε_{el}	Young's modulus, E, MPa
CM system Policril 590 + Fly Ash B					
90	1.15	0.30	0.18	0.12	9.7
85	2.04	0.30	0.10	0.20	10.2
75	0.61	0.31	0.05	0.26	2.4
65	0.38	0.31	0.08	0.23	1.6
CM system Latex 2012 + Fly Ash B					
90	5.13	0.28	0.16	0.12	42.8
85	10.21	0.30	0.10	0.20	51.0

75	11.50	0.28	0.09	0.19	60.6
65	4.42	0.29	0.14	0.15	29.3

Similar dependence occurs when using Fly Ash K as filler. The experimental results are presented in Figs. 10, 11 and Table 6. The samples based on Latex 2012 with Fly Ash K have significantly higher values of Young's modulus compared to the systems based on Policril 590. So, for Latex 2012-based samples with 65–85 % of Fly Ash K, the *E* values are 10–40 times higher compared to systems based on Policril 590, and maximal Young's modulus value of 91.7 MPa is observed for Latex 2012 + Fly Ash K 90 wt. %. Thus, it can be concluded that the type of polymer binder, as well as the filler content, have a significant effect on the mechanical properties of CM systems with fly ash fillers. The increase in the content of hard ash particles in the CM system promotes the strengthening of the samples, *i. e.*, the higher compression load is required to achieve the same values of sample deformation.

.However, it should be noted that Latex 2012-based samples, regardless of the ash type, have significantly higher ultimate load values: 7.2 times higher for samples with Fly Ash K and 6 times higher for samples with Fly Ash B compared to Policril 590-based system.

The obtained data correlate with the results represented by Wasekar et al.[12], who investigated systems using glass balls in the composition with nylon 6 and showed that fly ash (albeit in lower concentrations of 0–10 phr) significantly improves the mechanical characteristics of the composites. The results of our research demonstrate greater efficiency when using ash with different types of polymer matrices.

The given analysis of the obtained characteristics of the mechanical properties of experimental composites is important for determining the scope of their practical use.

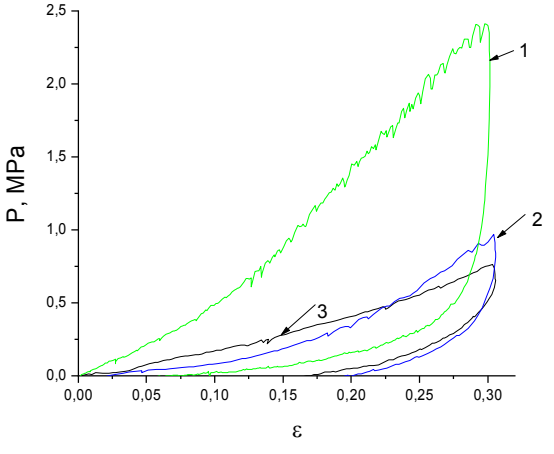


Fig. 10. Dependence of the strain on the load for CM system Policril 590 + Fly Ash K: 1 – 85 wt. % of ash; 2 – 75 wt. % of ash; 3 – 65 wt. % of ash

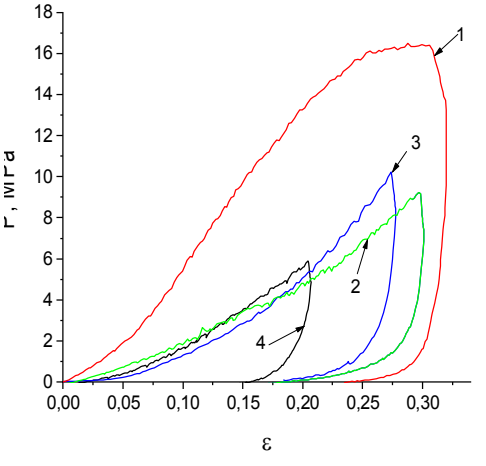


Fig. 11. Dependence of strain on load for CM system Latex 2012 + Fly Ash K: 1 – 90 wt. % of ash; 2 – 85 wt. % of ash; 3 – 75 wt. % of ash; 4 – 65 wt. % of ash

Table 6. Strength and elastic characteristics of samples using ash from the KurakhivskaTPP

Content of Fly Ash B, wt. %	Maximum load, *P*, MPa	ε_{total}	ε_{pl}	ε_{el}	Young's modulus, E, MPa
CM system Policril 590 + Fly Ash K					
85	2.4	0.30	0.07	0.23	10.4
75	0.97	0.30	0.07	0.23	4.2
65	0.76	0.30	0.04	0.26	2.9
CM system Latex 2012 + Fly Ash K					
90	16.50	0.31	0.13	0.18	91.7
85	9.25	0.30	0.10	0.20	46.3
75	10.30	0.27	0.07	0.20	51.5
65	5.90	0.20	0.07	0.13	45.4

The present studies are in line with the principle of modern materials science of the "composition-structure-properties" relationship. The results of the studies show the peculiarities of the composition, lyophilicity, and energy state of the particle surface of different types of filler. These features are manifested in the degree of interaction of fillers with latexes, determining the thickness of the outer surface layers of the binder and, accordingly, the thickness of the matrix layers between the ash particles. This is subsequently reflected in the physical and mechanical properties of the samples of the obtained composites. It is likely that with an increase in the layers of the polymer matrix, the elasticity and resilience of the material tend to increase, and the specific resistance to stresses at the ash-latex contacts arising under external pressure decreases.

Obviously, the mechanism of such differentiation of strength indicators requires further research as an important factor for the formation of polymer composite properties. Further research may include numerical modeling of the mechanical properties of composites, which will allow to optimize the composition of materials and reduce the costs of experimental tests.

4. Conclusions

1. The use of thermal energy waste as fillers is a promising direction for expanding the raw material base of production and regulating the properties of polymer composites.

2. At the creation of the composites with increased content of waste fillers, one should take into account the peculiarities of their genesis, particle size, and phase composition, and the energy state of the surface as a factor of interaction with the matrix-copolymer.

3. The peculiarities of the energy state and surface structure of the fly ash of two TPPs, and the differences in their interaction with the copolymer were revealed using a complex of physico-chemical and instrumental analysis methods.

4. According to the results of testing, it is possible to adjust the properties of polymer composites when varying the types and concentrations of fly ash. At the same time, the range of changes in indicators is as follows: water absorption 4.2–12.7 %, abrasion 0.02–0.06 g/cm^2, deformation under uniaxial compression up to 0.3, Young's modulus 1.6–97.1 MPa.

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ОСОБЛИВОСТІ ЗОЛИ ВИНОСУ ТЕС ЯК НАПОВНЮВАЧА КОМПОЗИТІВ

Анотація. *Об'єктом дослідження стали композиційні матеріали із використанням золи виносу Бурштинської та Курахівської ТЕС як наповнювачів і полімерних дисперсій Policril 590 та Latex 2012 як матриць. Визначено зв'язок складу різновидів золи виносу теплових електростанцій України з особливостями енергетичного стану поверхні дисперсних частинок наповнювача як фактора взаємодії зі зв'язуючим під час формування структури полімерних композитів. Оцінено вплив високої концентрації наповнювачів на формування порової структури та показники фізико-механічних властивостей композитів. Встановлено можливість регулювання властивостей композитів у такому діапазоні: водопоглинання 4,2–12,7 %, стираність 0,02–0,06 г/см^2, залишкова деформація 0,3–1,3, модуль Юнга 0,6–49,1 МПа.*

Ключові слова: *композит, наповнювач, зола виносу, латекс, склад, структура, властивості.*