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REGULAR ARTICLE

Influence of Fly Ash Type and Polymer Matrix on the Thermal Conductivity of Polymer Composites

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The paper presents the results of a study on the thermal insulation properties of polymer composites based on fly ash from thermal power plants. Aqueous dispersions of styrene-butadiene (Latex 2012) and acrylic (Policril 590) polymers were used as the matrix. A complex multifactorial dependence of the thermal conductivity of the composite materials on the type and properties of the ash, its content, the type and concentration of the polymer dispersion, density, porosity, and temperature was established. The decisive role of the pore structure in forming effective thermal insulation was demonstrated. It was found that a more developed specific surface area, higher wettability, and lower filler density contribute to the reduction of thermal conductivity. The lowest thermal conductivity was shown by composites containing fly ash with a filler concentration of 65 wt. % in combination with an acrylic matrix. The selected matrix exhibits a more consistent thermal conductivity profile within the studied temperature interval, indicating enhanced thermal stability. The results obtained allow us to determine the optimal conditions for the development of effective thermal insulation materials using industrial waste.

Keywords: Polymer composites, Thermal conductivity, Fly ash, Thermal insulation properties, Homogenization, Mechanical strength.

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1. INTRODUCTION

Fly ash is one of the most widespread by-products formed during coal combustion at thermal power plants (TPPs). The main types of these technogenic wastes include fly ash – fine particles carried by flue gases and captured by electrostatic precipitators – and bottom ash, which settles at the bottom of the furnace. The chemical composition of these materials typically includes oxides of silicon (SiO_2), aluminum (Al_2O_3), iron (Fe_2O_3), calcium (CaO), magnesium (MgO), among others, and their properties depend on the type of fuel used, combustion conditions, and gas cleaning systems. Due to their high thermal stability, pozzolanic properties, porosity, and active surface area, fly ash is considered not only a waste product but also a promising secondary raw material for various applications.

Against the backdrop of increasing environmental challenges and the search for solutions within the framework of the circular economy, the problem of fly ash and slag waste utilization is becoming particularly urgent. Globally, over 700 million tons of fly ash are generated annually, yet only a fraction is further utilized. For instance, in the United States, over 55 % of fly ash is deposited in ash disposal sites each year, leading to soil, water, and air pollution caused by dust emissions [1]. In Ukraine, as in many other countries, fly ash is one of the main industrial wastes produced at thermal power plants. The total accumulated volume of ash and slag waste is estimated at hundreds of millions of tons, with annual growth of around 6-7 million tons [2]. This is due to the widespread use of coal as a fuel at domestic TPPs and the specific features of their combustion technologies.

Scientists around the world are actively studying the potential applications of fly ash in various technologies. One of the most developed areas is the use of fly ash as a partial or full replacement for mineral fillers in construction materials. For example, in [3], it was shown that replacing sand with bottom ash in mortar compositions reduces the thermal conductivity of the material to 0.46 W/(m·K) while maintaining sufficient strength.

In addition to traditional concretes and mortars, fly ash is increasingly used in the development of lightweight porous thermal insulation materials. In particular, studies [4] have demonstrated the possibility of producing thermal insulation blocks from fly ash using foaming and pressure casting methods. The resulting samples had very low thermal conductivity – around 0.0511 W/(m·K), which is comparable to that of glass wool. Another interesting approach was presented in [5], where zeolite-like materials with thermal insulation properties (thermal conductivity of 0.153 W/(m·K)) were synthesized from fly ash. These materials are considered promising for use as coatings in energy-efficient buildings.

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In 2023, researchers demonstrated the feasibility of creating porous geopolymer materials from bottom ash using various foaming agents. These samples achieved a thermal conductivity of 0.32 W/(m·K) and a compressive strength of up to 6.86 MPa, making them competitive with commercial insulation blocks [6].

Another example of efficient fly ash utilization in insulation products is the development of composite panels based on fly ash and gypsum [7]. These materials combined low thermal conductivity with acoustic and fire-resistant properties. The sound absorption coefficient ranged from 0.3 to 0.8, fire resistance exceeded 50 minutes for panels with a thickness of 4 cm, and the thermal conductivity was comparable to commercial analogues. Leaching tests confirmed that the content of trace elements was within safe limits. These panels can be effectively used as interior wall partitions in buildings [7].

Fly ash is also used as a filler in polymer composite materials (PCMs). A study [8] showed that incorporating fly ash into epoxy polymer matrices improved mechanical properties, increased elastic modulus, enhanced interfacial bonding, and increased dielectric permittivity. Such composites exhibited thermal stability, energy storage and recovery capabilities, and lower thermal conductivity compared to the neat polymer matrix.

Another promising application of fly ash involves the development of specialized thermal insulation coatings and mixtures for the mining industry. For instance, in 2020, a fly ash-based material was developed for forming thermal insulation layers in mine workings. The study showed that such layers significantly reduced heat emission and stabilized the temperature field under complex geological conditions [9].

Given the broad range of potential fly ash applications and its availability as a secondary raw material, interest is growing in creating new composite materials with improved thermal insulation performance. Particularly promising is the combination of fly ash with polymer dispersions, especially latexes, which facilitate the formation of a porous structure and allow the regulation of the final properties of the materials. In this context, it becomes necessary to investigate how the type of fly ash, component ratios, and processing conditions affect the structure, physical-mechanical, and thermophysical properties of such composites.

The aim of this study is to develop and investigate the properties of thermal insulation materials based on fly ash from thermal power plants combined with aqueous polymer dispersions. The study focuses on evaluating their structure, porosity, thermal conductivity, and other performance characteristics. The relevance of this work is driven by the need to find environmentally safe and economically viable ways to utilize industrial waste, as well as to develop affordable insulation materials for use in construction and related industries.

2. MATERIALS AND METHODS

I As part of this study, composite materials based on a "copolymer–filler" system were investigated, in which fly ash from two Ukrainian thermal power plants – Burshtyn TPP (Ash B) and Kurakhiv TPP (Ash K) – was used as a functional filler. These ashes differ in origin and formation conditions: Kurakhiv TPP utilized anthracite from the Donetsk coal basin, while Burshtyn TPP used bituminous coal from the Lviv-Volyn basin. The difference in mineral composition is determined not only by the type of coal but also by the method of ash removal: dry at Kurakhiv TPP and wet at Burshtyn TPP.

According to the results of chemical analysis, the fly ash samples from both TPPs are classified as siliceous (or acidic) ashes, as indicated by the predominance of silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3) in their composition. However, significant differences were observed between the two samples in terms of the content of key components.

Kurakhiv ash contains more silicon dioxide – 51.5 wt. % compared to 46.1 wt. % in Burshtyn ash – whereas the aluminum oxide content is slightly lower: 15.98 wt. % versus 18.00 wt. %, respectively. This results in a higher SiO_2/Al_2O_3 ratio in Kurakhiv ash (3.2), indicating a more pronounced siliceous character, compared to 2.6 for Burshtyn ash.

A notable difference is also observed in iron oxide (Fe_2O_3) content: Burshtyn ash contains significantly more (22.2 wt. %) than Kurakhiv ash (14.2 wt. %), which may affect the color, thermal conductivity, and reactivity of the composite material.

Attention should also be paid to the content of alkali (primarily K_2O) and alkaline earth oxides (CaO, MgO). Their combined content in Kurakhiv ash is approximately 13.5 wt. %, compared to only 7.6 wt. % in Burshtyn ash. This difference may influence the hydrophilicity, gel-forming capacity, and film formation processes in latex-based composites.

The loss on ignition also differs significantly: Kurakhiv ash has virtually no loss (0.01 wt. %), while Burshtyn ash shows a loss of 1.49 wt. %, which may indicate greater compositional stability of Kurakhiv ash and a lower amount of organic or volatile impurities.

The polymer matrix used for composite fabrication was based on two types of aqueous dispersions: styrene-butadiene (Latex 2012) and acrylic (Policril 590). Both polymers are commercially available white-colored dispersions that differ in composition, viscosity, particle size, and film-forming temperature [10].

The preparation of composite samples was carried out using a standard laboratory procedure involving several consecutive steps. First, the filler and polymer dispersion were jointly subjected to mechanical activation in a ball mill for 20 minutes. This preliminary treatment improved system dispersion, activated the particle surfaces, and enhanced interfacial interaction between the filler and polymer matrix.

After homogenization, the mixture was poured into cylindrical molds of appropriate volume. The samples were cured at room temperature for 48 hours to complete initial hardening and stabilize the structure. Subsequent heat treatment involved gradual heating to 80 °C with a 1-hour hold at this temperature. The final step was cold pressing of the cylindrical samples (10 mm in diameter) at 5-10 MPa to achieve the required density, mechanical strength, and structural integrity.

The difference in the physicochemical properties of the fillers (Table 1) significantly affects the thermal insulation characteristics of the resulting composite materials.

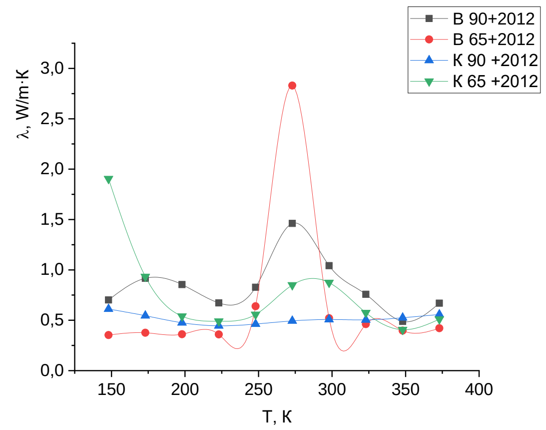
To evaluate the influence of the type of fly ash and its concentration on thermal conductivity, a series of composite samples with varying filler content was prepared. The thermal conductivity of the studied materials was measured using the IT-λ-400 device, which operates based on the dynamic calorimetry method. Measurements were carried out in the temperature range of 173 to 373 K, allowing the assessment of the thermal behavior of the samples under conditions close to real operation. The working principle of the device is described in detail in [11].

Table 1 – Physico-chemical properties of fillers

Filler	Specific Surface Area, BET, m^2/g	Wetting Angle, °	Surface Energy, mJ/m^2	Thermal Conductivity, W/m·K	Pycnometric Density, g/cm^3
Ash K	0.68	76	39.58	0.224	2.32
Ash B	3.45	69	51.67	0.207	1.82

3. RESULTS AND DISCUSSION

The results of the conducted experiments (Fig. 1) demonstrate a clear relationship between the type of fly ash and polymer matrix, the filler concentration in the composite, and the resulting thermal conductivity values of the materials.



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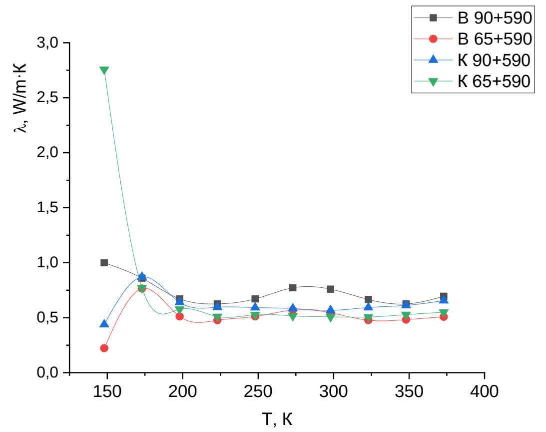

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Fig. 1 – Dependence of the thermal conductivity coefficient on temperature for the studied systems based on Latex 2012 (a) and Policril 590 (b)

The results show that the thermal conductivity of the investigated samples depends on temperature, the type of polymer dispersion, and the filler content. In all cases, a general trend is observed: thermal conductivity decreases with temperature down to approximately 250-270 K, after which the λ values either stabilize or exhibit local fluctuations.

For the samples based on Latex 2012 (Fig. 1a), the lowest thermal conductivity across the entire temperature range is observed in the ash B 65 wt. % + Latex 2012 system. This can be attributed to the higher specific surface area and more developed porosity of Burshtyn fly ash. The highest thermal conductivity is recorded for the ash K 65 wt. %+ Latex 2012 sample, which correlates with the less developed particle surface and higher density of Kurakhiv ash.

Samples based on Policril 590 (Fig. 1b) show less pronounced thermal conductivity peaks and generally exhibit more stable thermal behavior throughout the temperature range. The lowest λ values are also recorded for composites using Burshtyn ash at 65 wt. % filler content. In contrast, the highest thermal conductivity at low temperatures is observed in the ash K 65 wt. % + Policril 590 system, although its λ values gradually decrease and stabilize as the temperature rises.

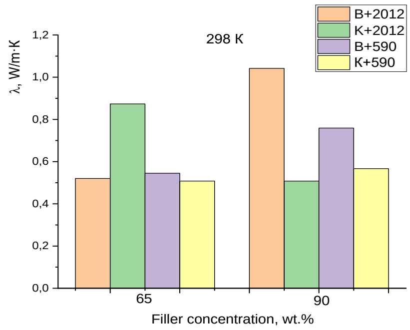
Thus, reducing the filler content from 90 to 65 wt. % leads to lower thermal conductivity in most cases. This is explained by the formation of a more pronounced porous structure and a reduction in the number of thermally conductive pathways within the composite. From the standpoint of thermal insulation efficiency, the most effective system was based on Latex 2012, especially when combined with Burshtyn fly ash.

Additionally, the influence of filler concentration on the thermal conductivity of the composites was examined at two characteristic temperatures – 298 K and 373 K. The results are shown in Figure 2.

Analysis of the histograms shows that increasing the filler content from 65 to 90 wt. % generally leads to an increase in thermal conductivity across most systems. The lowest λ values across the entire temperature range were observed in the composite based on Burshtyn TPP fly ash at 65 wt. % filler content and the acrylic matrix Policril 590. Conversely, the highest thermal conductivity values were recorded in samples containing 90 wt. % Kurakhiv fly ash, especially in systems using Latex 2012.

It is worth noting that increasing the temperature to 373 K results in a general rise in thermal conductivity for all samples. However, the relative increase is less pronounced in composites with the acrylic matrix (Policril 590), indicating greater thermal stability in terms of heat transfer performance.

To further analyze the influence of composition and structure on thermal conductivity, graphs were constructed showing the dependence of the thermal conductivity coefficient on the density of the studied samples (Figure 3). The results demonstrate a general trend of increasing thermal conductivity with increasing density, which can be explained by the reduction in air pore volume – the primary insulating component. At the same time, samples based on Burshtyn fly ash exhibit a slower increase in thermal conductivity, indicating a more effective insulating effect at equivalent density.



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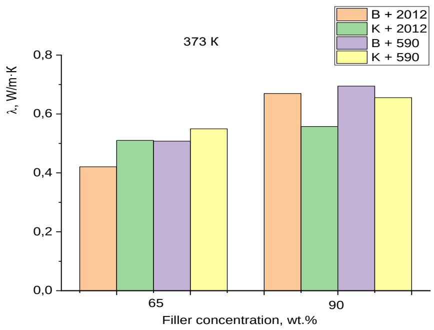

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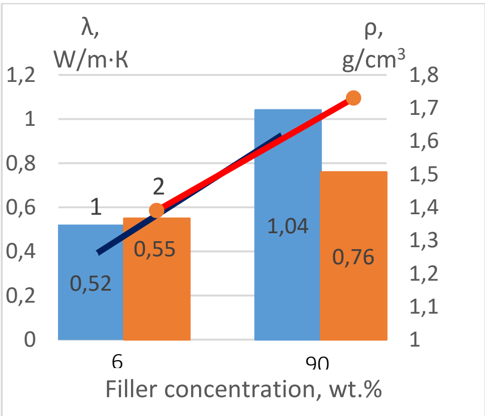
Fig. 2 – Dependence of thermal conductivity on filler concentration (at different temperatures) for the studied systems



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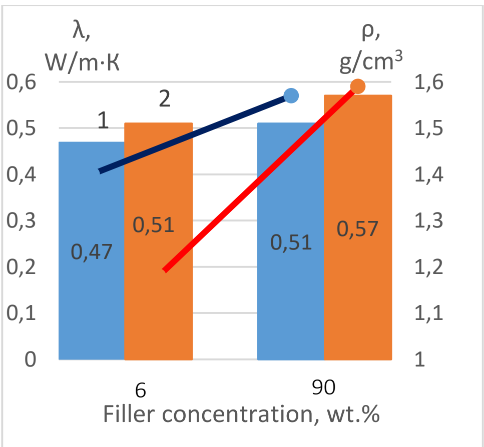

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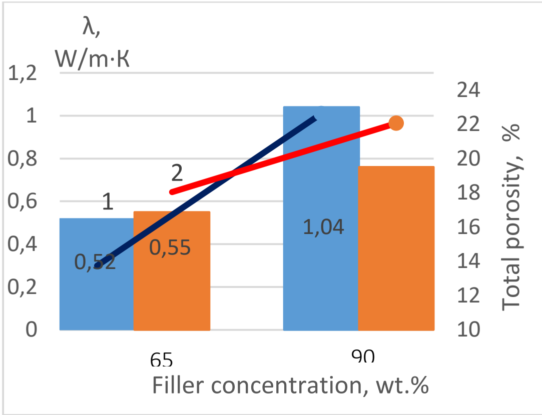
Fig. 3 – Dependence of thermal conductivity coefficient and composite density for systems with Ash B (a) and Ash K (b): 1 – Latex 2012, 2 – Policril 590

To clarify the influence of porosity on the thermal conductivity properties, the dependence of λ on sample porosity was analyzed (Figure 4). As expected, thermal conductivity decreases with increasing porosity. However, for samples filled with Kurakhiv TPP fly ash, this dependence is less pronounced, which may be attributed to the higher density and less developed microporosity of this ash.



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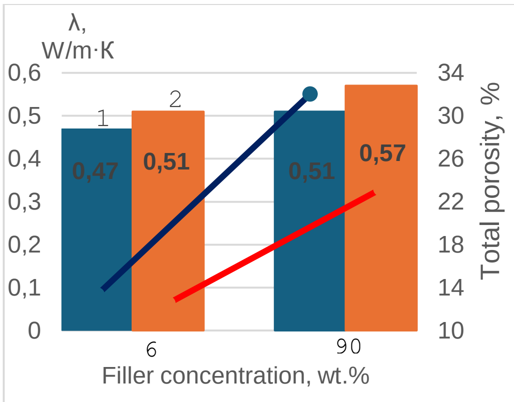

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Fig. 4 – Dependence of thermal conductivity and total porosity for composites with Ash B (a) and Ash K (b) in systems based on: 1 – Latex 2012, 2 – Policril 590

Additionally, it was found that the temperature-dependent behavior of thermal conductivity (Figure 1) corresponds well with the morphological characteristics of the fillers. In particular, the lowest λ values were observed in systems combining high porosity, low density, and strong wettability of filler particles by the matrix (Ash B + Latex 2012).

The results obtained indicate a complex, multifactorial dependence of the thermal conductivity of composite materials on the properties of the filler, its concentration, the type of polymer dispersion, and temperature. The lowest thermal conductivity values were recorded in samples containing 65 wt. % of Burshtyn fly ash in combination with the acrylic matrix Policril 590, which can be explained by a set of favorable physicochemical characteristics of this filler. Specifically, a higher specific surface area, improved wettability, and lower density contribute to the reduction of thermal conductivity, consistent with the findings reported in [5, 12].

An increase in fly ash content from 65 to 90 wt. % results in a rise in thermal conductivity, which is associated with the densification of the composite structure and a reduction in air pore volume. Therefore, lowering the filler content to 65 wt. % can be considered optimal in terms of the thermal insulation efficiency of the composites. Similar trends were noted in studies dedicated to porous construction materials based on fly ash [13].

Burshtyn fly ash demonstrated better insulation properties compared to Kurakhiv ash, which is attributed to its higher specific surface area (3.45 m^2/g), lower intrinsic thermal conductivity, and greater wettability. It is well established that an increase in filler surface area promotes composite porosity and reduces the number of thermally conductive pathways [7, 14].

The type of polymer matrix also significantly influences thermal conductivity. Systems based on Policril 590 showed more stable thermal behavior throughout the temperature range. This is likely due to the improved compatibility of the acrylic matrix with mineral particles and more uniform phase distribution, consistent with the results presented in [15, 16].

Thus, the key factors determining the thermal insulation performance of polymer composites based on fly ash include specific surface area, wettability, porosity, and filler concentration. Similar dependencies were observed in geopolymers and composites with inorganic matrices [1, 17], confirming the general applicability of the identified trends.

4. CONCLUSIONS

1. The type of fly ash has a significant effect on the thermal conductivity of the composites. Samples filled with Burshtyn TPP ash exhibited lower thermal conductivity values compared to those based on Kurakhiv TPP ash. This is attributed to the higher specific surface area (3.45 m^2/g vs. 0.68 m^2/g) and lower density (1.82 g/cm^3 vs. 2.32 g/cm^3) of Burshtyn ash.

2. Reducing the filler concentration from 90 wt. % to 65 wt. % leads to a noticeable decrease in the thermal conductivity of the materials. For instance, in the composite based on Latex 2012 and Burshtyn ash, the thermal conductivity was 0.081 W/(m·K) at 65 wt. % filler, compared to 0.103 W/(m·K) at 90 wt. %.

3. The type of polymer matrix also influences the thermal performance of the composites. Systems based on the acrylic dispersion Policril 590 exhibited more stable thermal conductivity values under temperature variation. The lowest λ value – 0.078 W/(m·K) – was recorded for the system containing 65 wt. % Burshtyn ash and Policril 590 at 298 K.

4. Porosity is a key factor determining the thermal insulation properties. In samples with higher total porosity (up to 42 %), thermal conductivity was reduced by 15-25 % compared to denser samples. This confirms the critical role of the porous structure in forming an effective thermal barrier.

5. The optimal combination of thermal insulation properties was achieved in composites using Burshtyn fly ash, the acrylic polymer dispersion Policril 590, and a filler content of 65 wt. %. These materials demonstrated low thermal conductivity values (0.078-0.081 W/(m·K)), acceptable density, and high potential for use as lightweight thermal insulation coatings.

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Вплив типу золи та матриці на теплопровідність полімерних композитів

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У статті представлено результати дослідження теплоізоляційних властивостей полімерних композитів на основі золи виносу. В якості матриці використані водні дисперсії стирол-бутадієнового (Latex 2012) та акрилового (Policril 590) полімерів. Встановлено, складну багатофакторну залежність теплопровідності композиційних матеріалів від типу та властивостей золи, її вмісту, типу та концентрації полімерної дисперсії, густини, пористості та температури. Доведено визначальну роль порової структури у формуванні ефективного теплозахисту. Встановлено, що більш розвинена питома поверхня, висока змочуваність та менша густина наповнювача сприяють зниженню теплопровідності. Композити з використанням золи при концентрації 65 мас.% наповнювача та акриловій матриці демонструють найнижчі значення коефіцієнта теплопровідності. Зазначена матриця демонструє термічно стабільну поведінку в межах досліджуваного температурного діапазону. Отримані результати дозволяють визначити оптимальні умови для створення ефективних теплоізоляційних матеріалів із використанням техногенних відходів

Ключові слова: Полімерні композити, Теплопровідність, Зола виносу, Теплоізоляційні властивості, Гомогенізація, Механічна міцність.