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Utilizing Fuel and Energy Sector Waste as Thermal Insulation Materials for Technical Buildings

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Abstract: The growing demand for sustainable construction materials has prompted intensive research into the potential reuse of waste from the fuel and energy sector as effective thermal insulation materials. This study examines the feasibility of utilizing ash–slag mixtures, fly ash, and aluminosilicates as insulation materials for technical buildings. These materials were selected due to their availability and potential to improve energy efficiency in construction. Practical tests were carried out to determine the thermal conductivity coefficients of various samples, which were produced using different cement mixtures as binders to ensure adequate structural strength. The results demonstrated that the use of industrial waste-derived materials not only provides satisfactory thermal insulation properties but also contributes to environmental sustainability by reducing the challenges associated with the disposal of industrial by-products. The study highlights the crucial role of cement as a binder, enhancing the mechanical strength and durability of the insulation samples. The integration of ash–slag mixtures, fly ash, and aluminosilicates into the construction sector may foster the adoption of more environmentally friendly building practices, thereby supporting a circular economy and mitigating the environmental impact of construction activities. The study showed that the lowest thermal conductivity coefficient (0.24 W/m·K) was achieved for mixtures containing fly ash and cement, while the highest value (0.30 W/m·K) was recorded in samples incorporating aluminosilicates. The obtained results confirm the effectiveness of fly ash as a cost-efficient additive that improves the thermal insulation properties of the material.

Keywords: sustainable technologies in buildings; thermal insulation materials; fuel and energy sector waste; circular economy; energy efficiency in buildings; construction process management; zero energy buildings; building energy

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1. Introduction

As Ukraine strives to enhance its energy independence, there is growing interest in the implementation of materials that not only provide adequate thermal insulation properties but also support the country's broader sustainable development goals [1]. The use of waste from the fuel and energy sector, such as ash–slag mixtures, fly ash, and aluminosilicates as insulation materials in construction, represents a strategic approach to achieving these objectives. These materials offer dual benefits, contributing to the development of a circular economy while addressing the urgent need for cost-effective and environmentally friendly insulation solutions [2].

The integration of these materials into the construction sector supports both short-term and long-term goals by reducing dependence on conventional insulation materials and limiting the environmental impact associated with the operation of new and existing buildings [2,3].

Thermal insulation materials play a key role in reducing energy consumption in buildings by limiting heat transfer between interior and exterior environments. They help maintain comfortable indoor temperatures, lower energy costs, and enhance the overall energy efficiency of buildings [4]. In particular, the use of waste from the fuel and energy sector, such as ash–slag mixtures, fly ash, and aluminosilicates, is emerging as an innovative insulation approach [4,5].

The choice of thermal insulation materials often depends on the type of building and its specific requirements. In residential buildings, the priority is comfort and cost-effectiveness, while commercial buildings focus on reducing operating costs and meeting energy certification standards [1,6]. Industrial and technical facilities, such as factories, laboratories, and utility buildings, require materials that combine high thermal performance with the durability necessary to withstand harsh operating conditions [7].

In residential construction, traditional insulation materials such as glass wool, mineral wool, and foam boards are commonly used. However, recycled materials such as fly ash and ash–slag mixtures demonstrate promising thermal insulation properties, making them a viable alternative [6].

Traditional materials, such as mineral wool, glass wool, or synthetic foams, are characterized by very good insulation properties, but they are produced from primary raw materials and often require energy-intensive manufacturing processes. In contrast, newly developed composites containing fly ash, ash–slag mixtures, and aluminosilicates achieve thermal conductivity within an acceptable range for technical insulation and represent a significant step toward sustainable construction.

The comparison of these two groups of materials not only helps to understand the current capabilities of available insulators but also highlights the contribution of this study to the development of knowledge, particularly regarding the use of industrial mineral waste as functional, inexpensive, and durable insulation components. The adopted methodology allows for a practical comparison of the insulation properties of new mixtures and their potential in the design of materials dedicated to technical facilities.

In terms of technical parameters, traditional insulation materials such as mineral wool and polystyrene are characterized by very low thermal conductivity values, typically ranging from 0.030 to 0.040 W/m·K. For comparison, the materials described in this study achieved values ranging from 0.24 to 0.30 W/m·K, which, although indicating lower insulation effectiveness than wool and polystyrene, are comparable to the thermal conductivity of ceramic hollow blocks or perforated bricks. This makes them suitable for application in the insulation of technical and industrial facilities. Nevertheless, their use offers significant ecological and economic benefits, including the reduction in industrial waste, lowering CO_2 emissions, and support for a circular economy. Therefore, these materials can represent a valuable solution in the context of insulating technical buildings, where mechanical strength and structural durability are also of key importance. Such parameters are considered promising, especially given that the tested materials were derived from industrial waste, are characterized by low production costs, and have a positive environmental impact. The thermal conductivity coefficient λ of different insulating and structural materials is summarized in Table 1.

Table 1. Comparison of the thermal conductivity coefficient λ of various insulating and structural materials.

Material	The Thermal Conductivity Coefficient λ, W/m·K	Reference
Sample: Cement + Fly Ash	0.240	[8]
Sample: Cement + Ash–Slag Mixture	0.249	[8]
Sample: Cement + Aluminosilicate	0.299	[8]
Structural Concrete (Reinforced Concrete)	≈1.7	[9]
Cement (Dry)	0.7–1.1	[10]
Mineral Wool	0.035–0.045	[11]
Polystyrene Foam (EPS/XPS)	0.030–0.040	[11,12]

In commercial buildings, thermal insulation plays a crucial role in reducing operational costs and meeting stringent energy efficiency standards. When fly ash and aluminosilicates are combined with cement as a binder, durable insulation materials with high thermal resistance and strength are produced. These composites can be applied to walls, floors, and roofs, enhancing the thermal envelope of commercial buildings [6,13]. By improving the thermal resistance of building partitions, these materials help maintain stable indoor temperatures and reduce long-term energy consumption. Moreover, their use supports sustainability efforts by reusing industrial waste that would otherwise require disposal.

Technical buildings such as data centers, control rooms, or research laboratories generate significant amounts of heat due to the presence of high-energy equipment. For these types of facilities, insulation materials must demonstrate exceptional thermal resistance and long-term durability. Ash–slag mixtures and aluminosilicates, combined with high-strength cement, provide insulation that meets these requirements while also offering fire resistance and sound absorption properties [7,14].

Cement is commonly used as a binder to enhance the structural integrity of insulation materials. The inclusion of cement in mixtures containing fly ash, ash–slag mixtures, or aluminosilicates imparts adequate compressive strength and resistance to mechanical loads to the resulting composites [15]. This is especially important in technical buildings, where insulation panels are exposed to more demanding operational and environmental conditions.

Modifying the stability characteristics of materials through thermochemical degradation is a particularly relevant approach in the context of sustainable construction [16]. This process involves the use of surface or underground generators to gasify coal or biomass, resulting in valuable by-products that can be reused [16,17]. During gasification, an artificial shell forms around the material, enhancing its structural integrity. By selectively melting a portion of the surface to a controlled depth, a protective layer is formed that serves as a barrier against environmental factors [18]. This layer prevents degradation caused by moisture, temperature fluctuations, and other external influences. As a result, the stability and durability of thermal insulation materials are significantly improved, allowing them to perform effectively over extended periods [16,19]. This innovative approach enhances both the performance and lifespan of insulation systems used in modern construction.

The use of waste from the fuel and energy sector as insulation materials not only reduces the amount of waste sent to landfills but also lowers the carbon footprint of the construction industry [19,20]. Fly ash and slag, for example, are by-products of coal combustion that can effectively replace virgin raw materials in insulation applications. This practice supports the principles of a circular economy and contributes to the achievement of sustainable development goals across various sectors [21]. Thermal conductivity is a key parameter in evaluating the effectiveness of insulation materials. Studies have shown that ash–slag and aluminosilicate mixtures exhibit low thermal conductivity, making them suitable for retaining heat during winter months and protecting interiors from overheating in the summer [22]. This reduces the demand for heating and cooling, ultimately lowering energy costs for building owners.

The use of fuel and energy sector waste as insulation materials is gaining importance not only in the context of technical buildings but also in residential, commercial, and industrial construction. As research progresses, the development of advanced insulation materials based on recycled content is likely to become a cornerstone of sustainable building practices. With the growing demand for environmentally friendly solutions, these materials offer an opportunity to improve energy efficiency while addressing large-scale waste management challenges.

The innovation of this study lies in the direct comparison of the thermal insulation properties of various materials derived from fuel and energy sector waste, conducted under standardized experimental conditions. Particular attention was given to the phase structure, particle morphology, and specific surface area of the analyzed materials. Additionally, the study combines the evaluation of thermal efficiency with a practical approach to the production technologies of materials intended for technical buildings. This integrated approach offers a new perspective on optimizing the use of waste in construction, supporting both energy efficiency and the implementation of circular economy principles.

2. Reference Background of the Thermal Insulation Materials for Buildings

Thermal insulation materials are essential components in construction, playing a key role in energy conservation and ensuring indoor comfort. Their function is to reduce the rate of heat transfer between the interior of a building and its external environment [23]. Insulation materials can be organic, such as wool or cellulose, or inorganic, such as fiberglass or mineral wool, and each type is characterized by different properties. The selection of an appropriate insulation material depends on factors such as the type of building, the climate, and the desired level of energy efficiency. The use of thermal insulation in construction dates back centuries, with early forms such as straw and clay being used in primitive structures. Modern insulation materials began to appear during the Industrial Revolution, with mineral wool and fiberglass introduced in the early twentieth century [1,23,24]. Since then, these materials have been refined to improve their insulating performance, fire resistance, and ease of installation, making them widely used in today's construction industry.

The most commonly used thermal insulation materials in modern construction include fiberglass, mineral wool, expanded polystyrene (EPS), extruded polystyrene (XPS), and polyurethane foam. Each of these materials has unique characteristics that influence its effectiveness in reducing heat loss. They differ in aspects such as R-value, which measures thermal resistance, as well as in moisture resistance, durability, and ease of application [23,25]. Fiberglass and mineral wool are especially valued for their affordability, non-combustibility, and excellent fire resistance properties, making them a safe choice for various building types. On the other hand, foam-based insulations such as EPS and XPS are highly appreciated for their versatility, low weight, and high R-values, which make them extremely effective thermal insulators [23,26]. Together, these materials offer a wide range of options for construction projects aiming to improve energy efficiency and meet specific insulation requirements [23,27].

In recent years, there has been a growing interest in sustainable insulation materials derived from natural and recycled sources. These include materials such as hemp, sheep's wool, and cellulose (recycled paper) [23,28]. Additionally, advancements in aerogel insulation, vacuum insulation panels (VIPs), and phase-change materials (PCMs) have improved thermal efficiency and expanded the range of environments in which insulation can be effectively applied. Such innovations contribute to the overall reduction in energy consumption in buildings and support the achievement of global sustainability goals.

The use of waste from the fuel and energy sector, such as fly ash, ash–slag mixtures, and aluminosilicates, as thermal insulation materials has gained significance due to the dual benefits of waste reduction and improved energy efficiency [29]. These materials are by-products of coal combustion and other industrial processes, they are readily available and possess favorable insulating properties [30]. After appropriate processing and combination with binders such as cement, they can form stable and durable insulation materials suitable for construction applications [31].

The ash–slag mixture is a material composed of ash and slag formed during coal combustion in power plants or boilers. It can be used in construction, especially in the production of cement or concrete, due to its binding properties. Fly ash is a material consisting of fine ash particles carried by flue gases during coal combustion. It is often collected using electrostatic precipitators and is also used in construction, particularly as an additive in cement and concrete mixtures. Aluminosilicate is a mineral composed of aluminum, silicon, and oxygen. It is commonly found in the ash remaining after coal combustion, especially in the case of lignite. Aluminosilicates are used in the production of various materials such as fiberglass, ceramics, and other construction products.

These materials are by-products not only from the extraction and processing of coal but also from the development of ore deposits and the thermochemical processing of biomass [19,32]. During biomass processing, coal is often added to increase the calorific value of the fuel, resulting in higher energy output. This process generates valuable by-products, including ash–slag mixtures and other mineral residues, which can be repurposed in various industrial applications [26,33]. These by-products possess beneficial properties that make them suitable for use in thermal insulation materials [34]. Their production aligns with sustainable practices by repurposing industrial waste, thereby reducing the environmental impact of mining activities and fuel production [33,35]. As a result, these materials contribute to more sustainable energy solutions while offering practical benefits for building insulation and other applications.

Traditional insulation materials, especially those produced from petrochemical sources, can have a significant environmental impact due to the extensive resource extraction and energy-intensive manufacturing processes involved. These materials often rely on non-renewable resources, resulting in a high carbon footprint and contributing to overall environmental degradation [33,36]. In contrast, using waste-derived materials for insulation supports a circular economy by repurposing by-products from industrial processes, such as ash and slag, which would otherwise be disposed of in landfills [1,37]. By replacing virgin resources with reclaimed materials, the construction industry can significantly reduce both the volume of landfill waste and the demand for newly extracted raw materials [26,38]. This shift not only minimizes the carbon footprint associated with building insulation but also promotes more sustainable and responsible resource management practices across the sector.

The effectiveness of thermal insulation materials is largely determined by their thermal conductivity and R-value. Studies have shown that materials such as fly ash and aluminosilicate can exhibit low thermal conductivity, making them effective insulators [26,39]. These materials can also improve the energy efficiency of buildings by retaining heat during colder months and helping to maintain lower indoor temperatures during warmer periods. This leads to reduced energy consumption for heating and cooling, ultimately lowering operational costs. As the demand for eco-friendly construction practices increases, the development of thermal insulation materials based on waste from the fuel and energy sector is expected to continue [40]. These materials show great promise due to their cost-effectiveness, availability, and contribution to environmental sustainability. Further research and development are expected to improve the thermal properties and application methods of waste-derived insulation materials, enabling their broader adoption in both residential and commercial construction projects worldwide.

The use of waste from the fuel and energy sector, such as slag, fly ash, and aluminosilicate, as thermal insulation materials for technical buildings has attracted significant attention in recent years due to its environmental and economic benefits. With the growing global demand for sustainable construction solutions, repurposing industrial by-products offers a practical way to reduce landfill disposal and minimize the carbon footprint of the construction industry. These materials, often abundant and low-cost, provide favorable insulation properties by reducing thermal conductivity, which contributes to improved energy efficiency in buildings. By replacing traditional insulation materials that rely heavily on non-renewable resources, waste-derived insulations support a circular economy and contribute to sustainability goals across various sectors. This is a real scientific and practical challenge that the author addresses while also attempting to assess the economic effectiveness of the materials discussed. Table 2 presents a comparison of the key properties of various binder types used in the production of thermal insulation materials.

Table 2. Comparison of the properties of various types of binders used in thermal insulation materials.

Binder Type	Setting Speed	Water Resistance	Cost	Environmental Friendliness	Compatibility with Ashes
Cement	Medium	High	Medium	Medium	High
Gypsum	Fast	Low	Low	High	High
Lime	Slow	Medium	Low	High	High
Magnesium-Based	Fast	Medium	Medium	Medium	Medium
Alkaline (Geopolymer)	Medium/Fast	High	Higher	High	High
Aluminosilicate	Fast	Medium	High	Medium	High

Among the best-performing insulation materials currently used in the construction industry are polyisocyanurate (PIR) panels, polyurethane (PUR) foams, extruded polystyrene (XPS) boards, and vacuum insulation panels (VIPs). Their thermal conductivity ranges from approximately 0.020 to 0.035 W/m·K, making them highly effective in reducing heat loss.

At the same time, these materials have numerous limitations: they are produced from petrochemical raw materials, have low resistance to high temperatures, are difficult to recycle, and generate a high carbon footprint. In comparison, the materials examined in this study, obtained from fuel and energy sector waste, show thermal conductivity values in the range of 0.24–0.30 W/m·K which, although lower in absolute performance, may be sufficient for many technical applications.

Due to their good structural stability, mechanical strength, and resistance to thermal degradation, these materials may serve as a viable alternative to commercial insulators, particularly in the context of sustainable construction. In this regard, the present study complements the existing body of knowledge with a group of solutions that combine technical efficiency with environmental and economic benefits.

3. Materials and Methods

This chapter presents a detailed characterization of the materials used in the study, as well as a description of the applied analytical methods. The purpose of the analyses was to assess the suitability of selected inorganic substances for use in composites with thermal insulation properties. In this context, the chemical composition, physical properties, and phase structure of four different materials were compared: Portland cement CEM I

42.5R, fly ash, an ash–slag mixture, and synthetic aluminosilicate. The selection of these materials was based on their wide availability, diversity in physicochemical properties, and application potential in lightweight, low-emission insulating composites.

Four groups of samples with different compositions were prepared for testing:

- Group 1: contains cement (50 g) and fly ash (200 g);
- Group 2: contains cement (50 g) and ash–slag mixture (200 g);
- Group 3: contains cement (50 g), ash–slag mixture (100 g), and fly ash (100 g);
- Group 4: contains cement (50 g) and synthetic aluminosilicate (200 g).

For each sample, the following parameters were determined: sample weight, thickness, side length, volume, density, and thermal conductivity coefficient λ. The measurement results are presented in Table 3.

Table 3. Chemical composition and physical properties of cement and additives.

Oxides	CEM I 42.5R	Fly Ash	Ash–Slag	Aluminosilicate
Chemical composition				
SiO_2	19.8	52	39.4	52.1
Al_2O_3	5.1	23	7.6	41.1
Fe_2O_3	2.6	13	1.3	4.3
CaO	64.1	6	42.1	0.07
MgO	1.6	2.5	6.1	0.2
SO_3	3.0	1.0	1.4	-
$Na_2O + K_2O$	0.8	2.9	1.1	0.9
Physical properties				
Density, g/cm^3	3.11	2.35	2.90	2.60
Grain size, µm	10–50	1–100	<50	1–163
Specific surface area, m^2/kg	385	250–600	350–500	12,000–15,000
Shape	irregular	spherical	irregular	irregular

In this study, all samples of fly ash, ash–slag mixture, and synthetic aluminosilicate were sourced from a single controlled industrial facility, which allowed for uniform analysis conditions. However, it should be emphasized that the chemical and phase composition of industrial waste may vary significantly depending on the source, combustion technology, and the type of primary raw material used. Therefore, in the subsequent stages of the research, the authors plan to include samples from different locations in order to assess the impact of this variability on the thermal insulation and mechanical properties of the composite materials.

The applied research methods enabled a comprehensive evaluation not only of the elemental and phase composition of the investigated materials but also of their physical properties, including density, specific surface area, and particle morphology. Particular emphasis was placed on the presence of amorphous phases and microspheres in the ash structure, as these features are critical to the thermal conductivity and porosity of the resulting composites [41].

A comparative analysis of the chemical composition, physical characteristics, and phase structure of the four studied materials—Portland cement CEM I 42.5R, fly ash, ash–slag mixture, and synthetic aluminosilicate—provides valuable insights into their potential for use in thermal insulation composites. The chemical composition reveals notable differences in the content of major oxides, which directly influence the materials' performance under service conditions.

Fly ash and synthetic aluminosilicate exhibit the highest SiO_2 content, measured at 52.0% and 52.1%, respectively. This high silica content favors the development of a distinctive microstructure and contributes to the formation of porous zones with low thermal conductivity. The elevated Al_2O_3 content observed in aluminosilicate (41.1%) and fly ash (23.0%) further enhances their pozzolanic reactivity.

In contrast, Portland cement CEM I 42.5R is characterized by a high CaO content (64.1%), which imparts strong hydraulic properties but limits its effectiveness as a standalone component in thermal insulation systems. The ash–slag mixture, with a chemical composition of 42.1% CaO and 39.4% SiO_2, represents an intermediate formulation that may serve effectively as a supplementary component.

From a physical perspective, synthetic aluminosilicate is particularly notable for its exceptionally high specific surface area (12,000–15,000 m^2/kg), which supports the formation of porous structures with superior insulating performance. Fly ash also demonstrates a relatively large surface area (250–600 m^2/kg), and its low density (2.35 g/cm^3), coupled with the spherical morphology of its particles, has a favorable impact on the rheological behavior of the mixtures. In contrast, Portland cement, with its higher density (3.11 g/cm^3) and lower specific surface area (385 m^2/kg), primarily serves as a structural binder, while simultaneously reducing the thermal insulation capacity of the composite material.

An important aspect of the analysis concerns the phase composition, particularly in the case of silica-rich fly ash of conventional origin. This material consists of three primary phases: crystalline, glassy, and amorphous. The crystalline phase includes a broad spectrum of minerals such as quartz (in both α and β forms), mullite ($3Al_2O_3 \cdot 2SiO_2$), hematite, magnetite, calcite, dolomite, anhydrite, free CaO, normal spinel ($MgAl_2O_4$), iron spinel ($FeAl_2O_4$), dicalcium ferrites, corundum, rutile or anatase (TiO_2), ettringite, opal, and others. These minerals originate from unburned coal residues, crystallization products of the molten phase, and high-temperature physicochemical transformations. Their presence can influence the chemical stability, rheological behavior, and thermal conductivity of the material.

The most relevant phase in terms of thermal insulation performance is the glassy phase, which can constitute between 50 percent and up to 90 percent of the total mass in conventional fly ash. This phase is amorphous in nature, with a chemical composition similar to basalt, primarily consisting of SiO_4 and AlO_4 tetrahedra. It also contains modifying oxides such as CaO, MgO, Na_2O, and K_2O. Two principal types of glass are distinguished: Type I, characterized by low density, a high SiO_2/Al_2O_3 ratio, and a low content of modifying oxides; and Type II, characterized by higher density, a low SiO_2/Al_2O_3 ratio, and a high content of modifying oxides. Type I glass generally forms larger spherical particles, whereas Type II is usually found as smaller, hollow microspheres.

The presence of microspheres in fly ash is one of the key features that enhances its value as a component in thermal insulation materials. Owing to their hollow structure and spherical geometry, microspheres significantly reduce the bulk density of the material and improve its workability. Furthermore, the incorporation of microspheres increases porosity and lowers thermal conductivity, which is highly desirable in the development of lightweight composites with insulating properties.

The amorphous phase, present only in trace amounts in the analyzed conventional silica-based fly ash, is mainly composed of dehydrated residues of clay minerals and small quantities of amorphous carbon (soot). Although its content is minimal, it may influence the binding mechanisms and the evolution of the microstructure in mixtures containing fly ash with elevated surface reactivity.

Synthetic aluminosilicate, due to its exceptionally high specific surface area, elevated content of reactive phases, and low density, represents the most effective component for thermal insulation applications. Fly ash, with its considerable glassy phase content and presence of microspheres, serves well as a supporting component—both structurally and functionally. Ash–slag mixtures may be used as complementary ingredients in composite systems designed to balance strength and insulation capacity. In contrast, Portland cement CEM I 42.5R, due to its high CaO content and substantial density, should be limited in insulation formulations and utilized primarily as a structural and binding agent rather than an active insulating material [42].

This study adopts a practical experimental approach combined with an analytical methodology to evaluate the thermal conductivity of materials using the thermal conductivity coefficient λ. Through direct measurements, the thermal properties of each material were determined, allowing for a precise assessment of their applicability in insulation systems. The use of the λ coefficient facilitates a detailed understanding of each material's contribution to energy efficiency in technical buildings through heat transfer reduction. The thermal conductivity coefficient λ is calculated as follows [43]:

$$\lambda = \frac{H \cdot q}{T_{\mathrm{H}} - T_{\mathrm{x}}}$$

where

λ—coefficient of the effective thermal conductivity, W/m·K;
H—thickness of the measured sample, mm;
q—density of the steady-state heat flux passing through the measured sample, W/m^2;
T_{H}—temperature of the hot surface of the measured sample, K;
T_{x}—temperature of the cold surface of the measured sample, K.

To evaluate the effectiveness of utilizing waste from the fuel and energy sector as thermal insulation materials for technical buildings, five samples of varying compositions were prepared for each type of material under investigation. The test specimens were fabricated in standardized dimensions of 100 mm by 100 mm, with varying heights. These samples were produced by combining the selected materials with Portland cement as a binder, following the principles of kinetic and static similarity to ensure uniformity in composition and structural integrity [43].

The samples were compacted and processed in accordance with standardized procedures governing the initial and final setting times of cement-based binders. This careful preparation ensured consistency across all specimens and provided a reliable foundation for subsequent testing. The curing period lasted 28 days, during which the cement matrix was allowed to harden and stabilize—an essential condition for obtaining accurate and reproducible measurements [41,43]. Throughout the curing phase, the samples were closely monitored to confirm the proper setting and uniform internal structure. This approach ensured that the thermal insulation properties of the materials could be assessed under consistent and standardized conditions.

Thermal conductivity measurements were performed using the IPT-MG4 "100" apparatus, adhering to precise methodological protocols to guarantee the reliability and repeatability of the results. The instrument was calibrated according to industry standards, which enabled accurate readings for all samples. This methodology facilitated a thorough evaluation of each material's ability to minimize heat transfer—one of the key indicators of its effectiveness as a thermal insulator. By accurately measuring the thermal conductivity coefficient, the potential application of the tested materials for insulation purposes in technical buildings was effectively assessed. The results offer valuable insight into their performance and highlight their relevance for enhancing energy efficiency in a variety of construction contexts. Photographic documentation of the experimental process, including sample preparation and testing apparatus, is presented in Figure 1.

(a) (b) (c)

Figure 1. Photographic documentation of the research process: (**a**) ash–slag and fly ash used as the raw material; (**b**) mold for casting samples and prepared samples; (**c**) IPT-MG4 "100" device for measuring thermal conductivity, featuring an electronic control unit and a heating element.

To determine the statistical significance of the observed differences in thermal conductivity (λ) values among the tested mixtures, a one-way analysis of variance (ANOVA) was performed at a significance level of $\alpha = 0.05$. Subsequently, a Tukey post-hoc test was conducted to assess differences between group pairs. The results of the analysis indicated that the variations in the composition of the mixtures had a statistically significant effect on the thermal insulation properties of the tested materials.

The device operates based on the principle of establishing a steady-state heat flow through a flat sample of defined thickness, directed perpendicularly to its face surfaces. This process involves a series of precise measurements, including the sample's thickness, heat flux density, and the temperatures of the opposite surfaces. By achieving a steady-state thermal condition, the device can accurately evaluate the heat transfer through the material. This data is critical for determining the material's thermal conductivity, which is essential for assessing its insulation performance. Overall, this method provides valuable insights into the material's behavior under conditions representative of real-world applications.

The measurement system is configured in accordance with an asymmetrical scheme, as specified by the Ukrainian standard DSTU 7076 (DSTU B V.2.7-105-2000) [44]. The stationary system of the device consists of a heating control unit and a cooling unit based on Peltier elements, a heat flux meter, platinum resistance temperature sensors, a signal conversion unit for sensor outputs, and a power supply. The Peltier elements are cooled using an integrated fan system.

The side panels of the setup include a power switch, grounding terminal, fuse, and sockets for connecting both the electronic control unit and the main power supply cable, as well as an eccentric locking mechanism. The electronic unit is powered via a dedicated connection from the setup. At the top of the assembly, a pressure screw equipped with a measurement device is used to determine sample thickness, along with a dynamometric mechanism with a ratchet for applying uniform clamping force to the sample.

The key variables examined in this study included the density, thickness, and composition of the fabricated samples. These parameters were systematically adjusted to analyze their impact on the material's overall thermal behavior. The final focus of the study was the thermal conductivity coefficient (λ), which is fundamental for evaluating the material's effectiveness as thermal insulation. This coefficient enables an accurate assessment of the material's insulating capability across various application surfaces.

4. Results and Discussions

The research involved the preparation of samples (Figure 1b, right) using a disassemblable steel mold featuring two rectangular parallelepiped cavities, each with internal dimensions of 100 mm (Figure 1b, left). In the initial phase, the samples were allowed to reach an early setting state that permitted their removal from the mold without structural damage. This phase typically lasted between 2 and 3 days. The second phase consisted of a 28-day curing period, during which the samples developed stable mechanical strength. Once the required strength was achieved, the samples were subjected to a drying process, which continued until mass stabilization was confirmed—defined as a change of less than 0.1% after two consecutive drying intervals of 0.5 h each.

To ensure accurate thermal conductivity measurements, the upper surface of each sample was polished to meet stringent specifications: both contact faces, intended to interface with the device's measurement plates, were required to be flat and parallel, with deviations in parallelism not exceeding ±0.5 mm. This meticulous surface preparation was essential for ensuring consistent and complete contact with the measurement apparatus, thereby minimizing potential sources of error.

Sample thickness was measured at four distinct points: each located approximately 50 ± 5 mm from a corner vertex and at the center of each edge. These measurements were performed using a high-precision caliper with an accuracy of ±0.1 mm. Such detailed dimensional control was critical to ensuring that the measured thermal conductivity values accurately reflected the true properties of the material. By maintaining consistent sample geometry, the study ensured reliable and reproducible results across all measurements. The precision of these preparatory steps had a direct impact on the reliability of the calculated thermal conductivity values, confirming that careful sample preparation was a fundamental component of the experimental methodology.

Following this preparation process, four groups of five samples each were produced with the following compositions:

Cement (50 g) + Ash–slag (200 g);

Cement (50 g) + Fly ash (200 g);

Cement (50 g) + Ash–slag (100 g) + Fly ash (100 g);

Cement (50 g) + Aluminosilicate (200 g).

Before commencing the main tests, the functionality of the measurement device was verified using a control sample made of organic glass, which was provided as part of the instrument's standard calibration kit (Figure 1c). This step ensured the accuracy and reliability of the device, confirming that it was operating within the specified parameters.

For the thermal conductivity measurements, the prepared samples were carefully placed on the cooling plate, and the heating plate was then positioned on top using a micrometer screw integrated with a dynamometric unit. This setup enabled precise control of the applied force, maintaining a uniform pressure of 2.5 kPa across each sample to ensure consistent contact between the sample and the measurement surfaces. Additionally, the thickness of each sample was measured at multiple points using the micrometer screw gauge, which provided highly accurate readings with a precision of up to 0.05 mm. These precise thickness measurements were critical for the subsequent calculation of thermal conductivity values.

Prior to initiating the direct measurements, essential data were entered into the electronic control unit, including the actual sample thickness, the target temperature for the cooling plate (Tx), and the set temperature for the heating plate (T_H). These input values were selected based on the sample's physical characteristics and the operational guidelines provided in the device's user manual. The settings for Tx and T_H were determined according to recommended values that vary depending on the sample's thickness and the estimated range of its thermal conductivity coefficient. This ensured that the device would operate under optimal conditions, thereby enhancing the accuracy and reliability of the measurements.

Once the measurement process began, the device's software precisely controlled both the heating and cooling units to achieve and maintain the specified surface temperatures—

T_H (hot side) and Tx (cold side)—with a high degree of accuracy (±0.2 °C). Maintaining these temperature conditions was essential for establishing a thermal steady state conducive to precise measurement. The system continuously monitored the heat flow through the sample and automatically adjusted the operation to maintain equilibrium. Upon reaching a stable heat flux, the device automatically calculated the thermal conductivity coefficient (λ) and thermal resistance (R). These values were recorded in the device's data archive, with the entire measurement process governed by integrated software to ensure consistency and data integrity. An audible signal indicated the successful completion of each measurement, confirming that the sample's thermal properties had been accurately determined.

The results of the study are presented in Table 4, providing a comprehensive overview of the measured values. The table includes thermal conductivity coefficients along with other relevant parameters for each tested sample, enabling a detailed comparison of the materials and highlighting their respective thermal performance characteristics.

Table 4. The results of the study of thermal conductivity of samples of insulating materials depending on the change in geometric dimensions and physical properties. x_i is the current value obtained from each individual sample; $\bar{x}$ is the average value for similar samples of a certain identical composition.

#	Sample Composition				Measured Sample Parameters								
	Cement (Grade 500), g	**Ash–Slag Mixture, g**	**Fly Ash, g**	**Alumo-Silicate, g**	**Weight, g**		**Thickness, mm**		**Side Length, mm**	**Volume, m³**	**Density, kg/m³**	**Thermal Conductivity Coefficient λ, W/m K**	
					x_i	$\bar{x}$	x_i	$\bar{x}$		$\bar{x}$	$\bar{x}$	x_i	$\bar{x}$
					201		13.9					0.25	
					198		13.6					0.238	
2	50	200	0	0	210	204	14.4	14	100	0.00014	1457	0.257	0.249
					204		14					0.257	
					207		14.1					0.243	
					187		15.9					0.228	
					181		15.5					0.235	
1	50	0	200	0	184	184	15.7	15.7	100	0.000157	1172	0.24	0.24
					178		15.2					0.247	
					190		16.2					0.25	
					207		14.2					0.254	
					195		14.4					0.26	
3	50	100	100		198	201	13.8	14.1	100	0.000141	1426	0.268	0.268
					204		14.5					0.276	
					201		13.6					0.282	
					223		15.9					0.283	
					220		15.8					0.29	
4	50	0	0	200	231	227	16.4	16.2	100	0.000162	1401	0.299	0.299
					234		16.5					0.308	
					227		16.4					0.315	

The visualization of the research findings on the variation in the thermal conductivity coefficient as a function of insulation mixture composition is presented in Figure 2. The graphical data illustrate how different proportions of components within the insulation mixtures influence thermal conductivity values. Analysis of the graphs reveals discernible trends in the increase or decrease in thermal conductivity depending on the content of cement, ash–slag, fly ash, and aluminosilicates in each sample. Notably, samples with a higher content of aluminosilicate exhibited lower thermal conductivity coefficients, confirming its effectiveness as a component in insulation materials. Furthermore, the inclusion of fly ash was observed to reduce thermal conductivity, thereby enhancing the insulating properties, particularly when used in combination with cement. The results presented in Figure 2 demonstrate that optimizing the composition of the insulation mixture can lead to significant improvements in thermal performance, which is essential for the development of efficient insulation materials for technical applications.

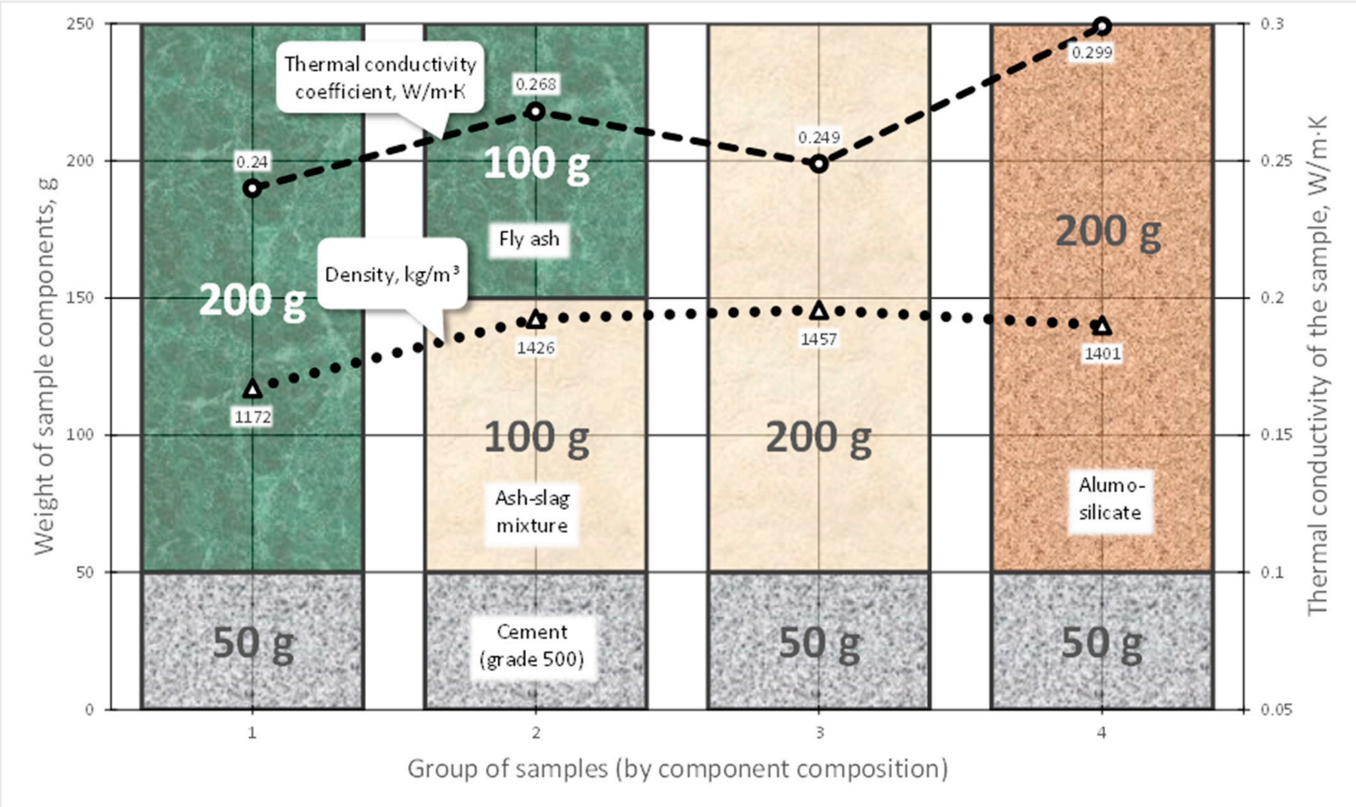

Figure 2. Dependence of thermal conductivity and sample density on the weight composition of components. All samples contain a constant amount of Portland cement (50 g) and a variable share of one of the following additives: fly ash, fly ash–slag mixture, or aluminosilicate. Thermal conductivity is represented by a dashed line, while density is indicated by a dotted line.

Visualizing the data through a chart provides a clear representation of the interdependence between sample composition, density, and thermal conductivity. The chart illustrates that the samples composed of fly ash and cement (Group 1) exhibit the lowest thermal conductivity, recorded at 0.24 W/m·K. Slightly higher thermal conductivity is observed in the samples made from ash–slag and cement (Group 3), with a value of 0.249 W/m·K. Interestingly, and somewhat counterintuitively, samples composed of equal parts fly ash, ash–slag, and cement exhibit an 8% higher thermal conductivity compared to the lowest values recorded in Groups 1 and 3. The highest thermal conductivity is observed in the samples made of cement and aluminosilicate (Group 4), reaching 0.299 W/m·K (Figure 3).

When analyzing density in relation to composition, the samples with a mixed filler (Group 2) demonstrate density values that fall between those of the single-component samples in Groups 1 and 3. This trend is consistent with the behavior of composite materials, whose properties typically reflect a balance between the characteristics of their individual constituents. Notably, a decrease in density observed in Group 4 samples, compared to the densities of Groups 2 and 3, is accompanied by a counterintuitive increase in thermal conductivity.

This phenomenon may be attributed to the influence of microstructural factors that extend beyond the material's bulk density. Thermal conductivity is affected by various factors, including the distribution and connectivity of pores, the presence of microspheres, the degree of cement hydration, and the quality of contact between components within the binding matrix. In some cases, materials with lower density may develop a more open and irregular porous structure, which can result in increased thermal conductivity. Thus, the overall insulating efficiency of a composite depends not only on its density but, more importantly, on the quality and architecture of its internal structure.

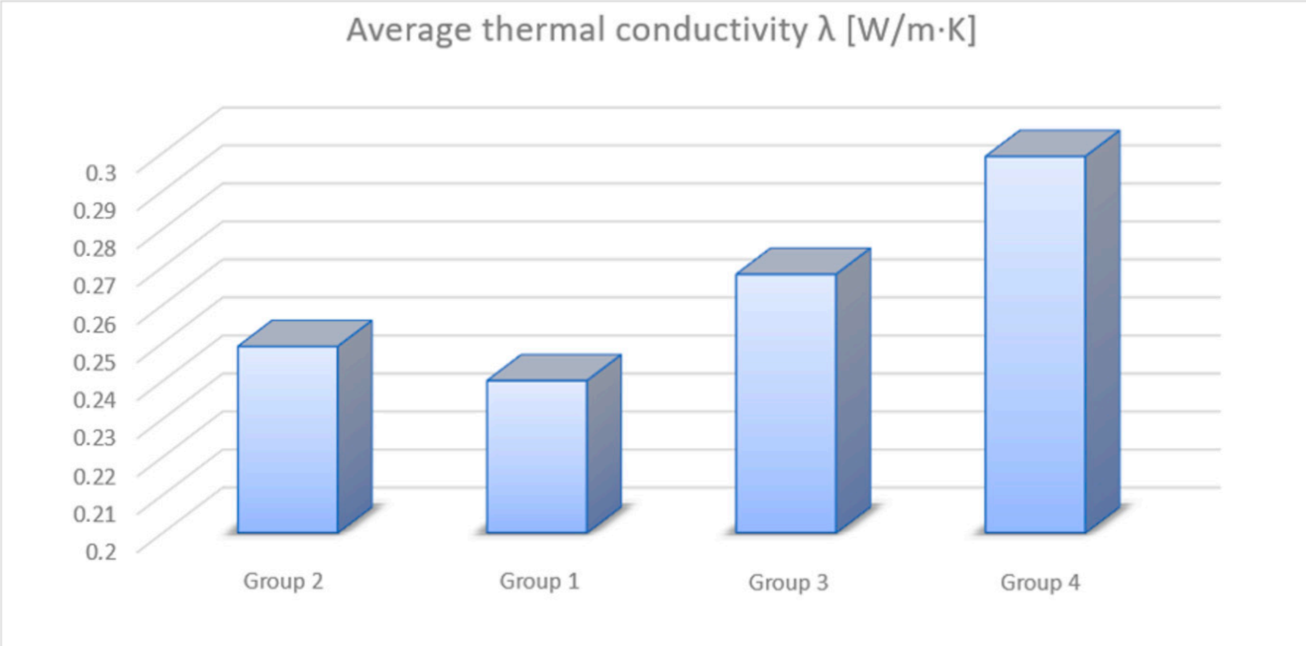

Figure 3. Comparison of the average thermal conductivity coefficient (λ) for different mixture compositions.

This unexpected outcome suggests that factors beyond density alone—such as microstructural configuration and specific interactions between components—may significantly influence the thermal properties of the tested samples. The improvement in the thermal insulation properties of the investigated materials results from the synergistic action of several physicochemical mechanisms. A key role is played by the presence of microspheres in fly ash, which, due to their hollow and spherical structure, reduce the bulk density of the composite and limit heat transfer. Additionally, glassy phases rich in silica and alumina contribute to the development of a porous and irregular microstructure, acting as a barrier to heat conduction. Moreover, the high specific surface area of aluminosilicates promotes an intense pozzolanic reaction with calcium ions released from cement hydration, leading to the formation of additional hydration products and the filling of microvoids. This process reduces the development of heat transport channels and improves the compactness of the structure. Collectively, these mechanisms define the overall thermal insulation efficiency of the composite.

Ash–slag, although the second-best performing material in terms of thermal conductivity, presents certain limitations due to its significantly higher density—over 22% greater than that of fly ash. This higher density may contribute to additional structural load, which can be a limiting factor in applications where lightweight materials are essential. Nonetheless, its comparable thermal performance makes ash–slag a viable alternative when weight constraints are not critical.

The results obtained in the present study are consistent with those reported by [43], who observed thermal conductivity values ranging from 0.26 to 0.31 W/m·K in panels composed of fly ash and lime. Similar values (0.22–0.28 W/m·K) were reported by Zhao et al. [43,45] for fly ash–perlite composites. In comparison, the best-performing samples in our study (fly ash + cement) achieved a thermal conductivity of 0.24 W/m·K, confirming the effectiveness of the proposed formulation.

Similarly, the findings of Kioupis et al. [46] for geopolymer mixtures with perlite indicate comparable thermal insulation properties, while emphasizing the critical influence of both micro- and macropore structures on thermal conductivity. The comparison of results underscores that industrial waste materials—particularly fly ash—can serve as a practical and effective alternative to commercial insulation products, offering both high performance and significant environmental advantages [46,47].

In future studies, the authors plan to expand their research by investigating the thermal conductivity of samples incorporating various additional materials, such as clay, sand, lime, lignin, and others. This exploration will provide a broader understanding of how these components influence the insulating properties of the resulting mixtures. Furthermore, experiments will be conducted using different mass fractions of these additives, allowing for a detailed assessment of how varying component ratios affect both thermal conductivity and overall material performance. The objective of these investigations is to identify optimal formulations for improved insulation efficiency, tailoring material compositions to meet specific application requirements.

In the context of long-term material durability, it is essential to consider potential risks associated with the use of waste-derived components such as fly ash, ash–slag mixtures, and aluminosilicates. The literature suggests that some of these additives may, over time, contribute to structural degradation through mechanisms such as ion leaching, microcracking, or uneven hydration processes. Although the present study did not include an analysis of aging effects, this issue will be addressed in subsequent research phases, particularly with regard to the performance of the material under technical operating conditions.

5. Conclusions

Based on the conducted research, it has been confirmed that the composition of the mixtures plays a crucial role in determining their thermal insulation properties. The lowest thermal conductivity (0.240 W/m·K) was recorded for samples containing fly ash and cement (Group 1), while the highest value (0.299 W/m·K) was observed in mixtures composed of cement and aluminosilicate (Group 4). This represents a nearly 20% difference, highlighting the significant influence of material composition on thermal performance.

In comparison, conventional concrete has a typical thermal conductivity of approximately 1.7 W/m·K, meaning that the Group 1 mixture provides a reduction in heat transfer of over 85%. This directly translates into significant energy savings and lower operational costs for buildings, particularly in terms of heating and cooling in technical or industrial applications.

The lowest recorded thermal conductivity coefficient was 0.24 W/m·K (fly ash with cement), while the highest was 0.30 W/m·K (aluminosilicate with cement). This demonstrates the significant influence of the type of industrial waste used and its proportion in the composite on the thermal insulation properties.

Structurally, fly ash exhibits low density and a porous structure, which enhances its thermal insulation properties. Although ash–slag-based mixtures demonstrated similar thermal conductivity to fly ash, their density was over 22% higher, which may be a limitation in applications where weight reduction is essential. Interestingly, some mixed compositions (Group 3) showed unexpectedly higher thermal conductivity values, suggesting that not all component combinations lead to beneficial synergistic effects.

Moreover, the results showed no clear correlation between density and thermal conductivity—in some cases, samples with lower density displayed higher thermal conductivity. This indicates that the interactions between components, rather than their individual properties, may have a dominant influence on overall thermal performance.

From an economic perspective, incorporating industrial by-products such as fly ash and ash–slag significantly reduces the cost of raw materials and contributes to a lower embodied energy in the material. The use of lightweight, insulating mixtures can reduce energy demand during building operations, leading to long-term financial savings. Additionally, such solutions support circular economy goals and reduce CO_2 emissions, making them not only cost-effective but also environmentally sustainable.

Given the above, fly ash emerges as the most promising component for the production of lightweight and thermally efficient insulating materials in construction. Future studies will focus on optimizing material formulations by introducing additional components such as clay, lime, sand, and lignin. These efforts aim to further enhance thermal performance and economic viability for a wide range of technical building applications.

In future research, the incorporation of lightweight additives of both natural and industrial origin is also planned, including expanded perlite, cellulose fibers, lignin-based biofillers, and amorphous silica. These materials exhibit very low thermal conductivity and have a beneficial effect on the porous microstructure of composites, without compromising their structural integrity. The use of perlite in combination with fly ash has been shown to achieve thermal conductivity values below 0.20 W/m·K. Such solutions could enable further optimization of the thermal insulation properties of the studied mixtures without the need for petrochemical-based additives.

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References

1. Naumenkova, S.; Mishchenko, V.; Mishchenko, S. Key Energy Indicators for Sustainable Development Goals in Ukraine. *Probl. Perspect. Manag.* **2022**, *20*, 379–395. [CrossRef]
2. Khan, Z.; Khan, F.A.; Khan, A.U.; Hussain, I.; Khan, A.; Shah, L.A.; Khan, J.; Badrashi, Y.I.; Kamiński, P.; Dyczko, A.; et al. Climate-Streamflow Relationship and Consequences of Its Instability in Large Rivers of Pakistan: An Elasticity Perspective. *Water* **2022**, *14*, 2033. [CrossRef]
3. Beshta, O.; Fedoreyko, V.; Palchyk, A.; Burega, N. Independent Power Supply of Menage Objects Based on Biosolid Oxide Fuel Systems. *Power Eng. Control Inf. Technol. Geotech. Syst.* **2015**, *33*, 39. [CrossRef]
4. Cry, C.M. The Potential Use of Waste (Ash) Materials for EIFS Insulation and Related Components. *Fuel Energy Abstr.* **1996**, *37*, 187. Available online: https://www.researchgate.net/publication/294850101 (accessed on 2 May 2025). [CrossRef]
5. Kicki, J.; Jarosz, J.; Dyczko, A.; Puszcza, H. The Economic and Technical Aspects of Mine Closure in Poland. In Proceedings of the 14th International Symposium on Mine Planning and Equipment Selection (MPES 2005), Banff, AB, Canada, 1–3 November 2005.
6. Jankovic, L. Renewable Energy. In *Designing Zero Carbon Buildings*, 2nd ed.; Routledge: Abingdon, UK, 2024; pp. 195–208. [CrossRef]
7. Adekanye, O.G.; Davis, A.; Azevedo, I.L. Federal Policy, Local Policy, and Green Building Certifications in the U.S. *Energy Build.* **2020**, *209*, 109700. [CrossRef]

8. Yuan, J.; Farnham, C.; Emura, K. Optimal Combination of Thermal Resistance of Insulation Materials and Primary Fuel Sources for Six Climate Zones of Japan. *Energy Build.* **2017**, *153*, 403–411. [CrossRef]
9. Restuccia, L.; Reggio, A.; Ferro, G.A.; Tulliani, J.-M. New Self-Healing Techniques for Cement-Based Materials. *Procedia Struct. Integr.* **2017**, *3*, 253–260. [CrossRef]
10. Latif, E.; Bevan, R.; Woolley, T. *Thermal Insulation Materials for Building Applications*; ICE Publishing: London, UK, 2019. [CrossRef]
11. Loftus, J.J. *NBS Report No. 9988*; Noncombustibility of Mineral Wool and Glass Fiber Insulation Materials. National Bureau of Standards: Washington, DC, USA, 1969.
12. Tkaczewska, E.; Malata, G. Properties of the Cement, Slag and Fly Ash Mixture Composition Corresponding to CEM II/C-M and CEM VI. *Mater. Proc.* **2023**, *13*, 11. [CrossRef]
13. Chmura, D.; Jagodziński, A.M.; Hutniczak, A.; Dyczko, A.; Woźniak, G. Novel Ecosystems in the Urban-Industrial Landscape–Interesting Aspects of Environmental Knowledge Requiring Broadening: A Review. *Sustainability* **2022**, *14*, 10829. [CrossRef]
14. Abdrakhimov, V.Z. Environmental Management, Economic and Practical Aspects of the Use of Waste from the Fuel and Energy Complex in the Production of Thermal Insulation Materials. *Econ. Gov. Law Basis* **2021**, *1*, 11–16. [CrossRef]
15. Bieda, B.; Skalna, I.; Gaweł, B.; Grzesik, K.; Henclik, A.; Sala, D. Life Cycle Inventory Processes of the Integrated Steel Plant (ISP) in Krakow, Poland—Continuous Casting of Steel (CCS): A Case Study. *Int. J. Life Cycle Assess.* **2018**, *23*, 1274–1285. [CrossRef]
16. Rabbat, C.; Awad, S.; Villot, A. Towards the Production of High Added-Value Products from the Pyrolysis and Steam Pyro-Gasification of Five Biomass-Based Building Insulation Materials at End-of-Life. *Waste Biomass Valorization* **2023**, *14*, 2061–2083. [CrossRef]
17. Fedoreiko, V.S.; Rutylo, M.I.; Iskerskyi, I.S.; Zahorodnii, R.I. Optimization of Heat Production Processes in the Biofuel Vortex Combustion Systems. *Nauk. Visn. Nats. Hirnych. Univ.* **2020**, *6*, 83–88. [CrossRef]
18. Dychkovskyi, R.O. Forming the Bilayer Artificially Created Shell of Georeactor in Underground Coal Well Gasification. *Nauk. Visn. Nats. Hirnych. Univ.* **2015**, *5*, 37–42.
19. Fedoreiko, V. Distributed Energy Generation Based on Jet-Vortex Bioheat Generators. *E3S Web Conf.* **2024**, *567*, 01001. [CrossRef]
20. Norouzi, M.; Haddad, A.N.; Jiménez, L.; Hoseinzadeh, S.; Boer, D. Carbon Footprint of Low-Energy Buildings in the United Kingdom: Effects of Mitigating Technological Pathways and Decarbonization Strategies. *Sci. Total Environ.* **2023**, *882*, 163490. [CrossRef]
21. Latif, E.; Bevan, R.; Woolley, T. Retrofit, Renovation and Fuel Poverty Initiatives: Insulation Materials. In *Thermal Insulation Materials for Building Applications*; ICE Publishing: London, UK, 2019; pp. 155–180. [CrossRef]
22. Lewicka, D.; Zarębska, J.; Batko, R.; Tarczydło, B.; Woźniak, M.; Cichoń, D.; Pec, M. Circular Economy in the European Union. In *Circular Economy in the European Union: Organisational Practice and Future Directions in Germany, Poland and Spain*; Routledge: London, UK, 2023; pp. 21–267. [CrossRef]
23. Borowicz, M.; Paciorek-Sadowska, J.; Lubczak, J.; Czupryński, B. Biodegradable, Flame-Retardant, and Bio-Based Rigid Polyurethane/Polyisocyanurate Foams for Thermal Insulation Application. *Polymers* **2019**, *11*, 1816. [CrossRef]
24. Lewicka, B.; Lewicka, D. Environmental Risk Management in the Context of Environmental Management Systems for Agriculture Based on the ISO 14001:2015 Standard. *Acta Innov.* **2019**, *33*, 63–72. [CrossRef]
25. Smith, R.E.; Alcott, J.M.; Mazor, M.H. Design Considerations for Sustainable Extruded Polystyrene (XPS) Thermal Insulation. In *Next-Generation Thermal Insulation Challenges and Opportunities*; ASTM International: West Conshohocken, PA, USA, 2014; pp. 1–12. [CrossRef]
26. Aleksakhin, A.; Sala, D.; Golovin, K.; Kovalev, R. Reducing Energy Costs for Pipeline Transportation. *Transp. Res. Procedia* **2021**, *57*, 24–32. [CrossRef]
27. Laustsen, J. *Energy Efficiency Requirements in Building Codes, Energy Efficiency Policies for New Buildings*; International Energy Agency: Paris, France, 2008. Available online: https://iea.blob.core.windows.net/assets/3783f5e8-b14c-4c18-b04c-aab7c59d6e92/Building_Codes.pdf (accessed on 29 April 2025).
28. Beshta, O.S.; Fedoreiko, V.S.; Balakhontsev, O.V.; Khudolii, S.S. Dependence of Electric Drive's Thermal State on Its Operation Mode. *Nauk. Visn. Nats. Hirnych. Univ.* **2014**, *6*, 67–72.
29. Worbs, H. Utilization of Energy Code Compliance Procedures for the Prediction of Commercial Building Annual Fuel Consumption. In *Thermal Insulation: Materials and Systems*; ASTM International: West Conshohocken, PA, USA, 1987; pp. 8–20. [CrossRef]
30. Dyczko, A. Thin Coal Seams, Their Role in the Reserve Base of Poland. In *Technical, Technological and Economical Aspects of Thin-Seams Coal Mining. International Mining Forum 2007*; CRC Press: London, UK, 2007; pp. 81–87. [CrossRef]
31. Dudek, M. The Model for the Calculation of the Dispersed Iron Ore Resource Purchase Cost in the World Class Manufacturing (WCM) Logistics Pillar Context. *Metalurgija* **2014**, *53*, 567–570.
32. Fedoreiko, V.S.; Luchko, M.R.; Iskerskyi, I.S.; Zahorodnii, R.I. Enhancing the Efficiency of Energy Generation Systems Based on Solid Biofuels: Technical and Economic Aspects. *Nauk. Visn. Nats. Hirnych. Univ.* **2019**, *2*, 94–100. [CrossRef]

33. Osman, A.I.; Farghali, M.; Dong, Y.; Kong, J.; Yousry, M.; Rashwan, A.K.; Chen, Z.; Al-Fatesh, A.; Rooney, D.W.; Yap, P.-S. Reducing the Carbon Footprint of Buildings Using Biochar-Based Bricks and Insulating Materials: A Review. *Environ. Chem. Lett.* **2024**, *22*, 71–104. [CrossRef]
34. Dudek, M.; Pawlewski, P. Implementation of Network Oriented Manufacturing Structures. In *Lecture Notes in Computer Science*; Springer: Berlin/Heidelberg, Germany, 2010; pp. 282–291. [CrossRef]
35. Kosenko, A.; Khomenko, O.; Kononenko, M.; Myronova, I.; Pazynich, Y. Raises Advance Using Borehole Hydraulic Technology. *E3S Web Conf.* **2024**, *567*, 01008. [CrossRef]
36. Winkless, L. Biobased Polyurethane Foams Outperform Those Made from Petroleum. *Mater. Today* **2023**, *67*, 11–12. [CrossRef]
37. Dychkovskyi, R.; Dyczko, A.; Borojević Šoštarić, S. Foreword: Physical and Chemical Geotechnologies—Innovations in Mining and Energy. *E3S Web Conf.* **2024**, *567*, 00001. [CrossRef]
38. Dudek, M. Utilisation of Simulation Modelling to Coordinate of Distributed Logistic Resources. In *Congress Proceedings—CLC 2012: Carpathian Logistics Congress*; TANGER Ltd.: Ostrava, Czech Republic, 2012; pp. 151–159.
39. Srivastava, N.; Gupta, B.; Gupta, S.; Danquah, M.K.; Sarethy, I.P. Analyzing Functional Microbial Diversity. In *Microbial Diversity in the Genomic Era*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 79–102. [CrossRef]
40. Polyanska, A.; Pazynich, Y.; Mykhailyshyn, K.; Babets, D.; Toś, P. Aspects of Energy Efficiency Management for Rational Energy Resource Utilization. *Rud. Geol. Naft. Zb.* **2024**, *39*, 13–26. [CrossRef]
41. Pyzalski, M.; Białoskórski, J.; Walasek, E. Reaction between Carbon Fibres and Molten Silicon: Heat Determination Using DTA. *J. Therm. Anal.* **1986**, *31*, 1193–1196. [CrossRef]
42. Durczak, K.; Pyzalski, M.; Pilarski, K.; Brylewski, T.; Sujak, A. The Effect of Liquid Slurry-Enhanced Corrosion on the Phase Composition of Selected Portland Cement Pastes. *Materials* **2021**, *14*, 1707. [CrossRef]
43. Zhao, P.; Ji, Y.; Ren, Q.; Li, X.; Vandeginste, V. On Thermal Insulation Properties of Various Foaming Materials Modified Fly Ash Based Geopolymers. *Polymers* **2023**, *15*, 3254. [CrossRef]
44. *DSTU B V.2.7-105:2000*; Building Materials. Materials and Products. Method for Determining Thermal Conductivity and Thermal Resistance Under Stationary Thermal Regime. State Committee for Construction, Architecture and Housing Policy of Ukraine: Kyiv, Ukraine, 2000. (In Ukrainian)
45. Mizuno, M.; Kokai, T.; Koho, J. Method and Apparatus for Thermal Decomposition of Waste Plastics for Fuel Manufacturing. *Fuel Energy Abstr.* **2003**, *44*, 121.
46. Kioupis, D.; Skaropoulou, A.; Tsivilis, S.; Kakali, G. Properties and Durability Performance of Lightweight Fly Ash Based Geopolymer Composites Incorporating Expanded Polystyrene and Expanded Perlite. *Ceramics* **2022**, *5*, 821–836. [CrossRef]
47. Saik, P.; Cherniaiev, O.; Anisimov, O.; Dychkovskyi, R.; Adamchuk, A. Mining of Non-Metallic Mineral Deposits in the Context of Ukraine's Reconstruction in the War and Post-War Periods. *Min. Miner. Depos.* **2023**, *17*, 91–102. [CrossRef]