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Use of fly ash and ground tuff as pozzolanic additives in lightweight structural

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ABSTRACT

This paper investigates the effect of partial replacement of cement with fly ash and ground volcanic tuff on the physical and mechanical properties of concrete. The main focus is on the changes in average density and compressive strength at different contents of replacement materials (from 10% to 35%). The investigated concrete composition (27PPPF) without admixtures has an average density of 1925.5 kg/m³ and compressive strength of 40.1 MPa. The results show that when fly ash is added, the concrete strength first increases, reaching a maximum value of 41.6 MPa at 10% cement replacement and then decreases to 29.1 MPa at 35% replacement. A similar trend is observed when tuff is introduced, but the peak strength (40.7 MPa) is also reached at 10% replacement, after which the strength gradually decreases to 27.9 MPa at 35%. The average density of the specimens changes insignificantly, being in the range of 1910.4-1928.5 kg/m³, which indicates that the dense structure of the concrete is maintained. Thus, the optimum content of fly ash and tuff in the concrete composition is 10-15%, as these values provide the best mechanical characteristics. Higher dosages of substitutes result in lower strength due to thinning of cement stone and lack of binding properties. This study confirms the possibility of using fly ash and volcanic tuff as effective pozzolanic additives to improve the environmental friendliness and sustainability of concrete.

Keywords: fly ash, pozzolanic effect, tuff, binder, lightweight structural concrete.

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Introduction

The use of fly ash from CHP (combined heat and power plant) waste and natural pozzolans in concrete composition as a partial replacement of cement plays an important role in the development of sustainable construction. Cement production is one of the largest sources of CO_2 emissions in the world, and its replacement with secondary and natural materials can significantly reduce the carbon footprint. Fly ash, a by-product of coal combustion, not only reduces the need for clinker cement but also improves the properties of concrete, increasing its strength and durability. Pozzolans such as volcanic tuff and zeolite, reacting with calcium hydroxide formed during cement hydration, promote the formation of additional amounts of strong calcium silicate hydrates, which increases the durability of structures [[1], [2], [3]].

The environmental advantages of such replacement are obvious: utilization of fly ash reduces the volume of waste that would otherwise accumulate in landfills, polluting soil and water, and the use of pozzolans reduces limestone mining and energy consumption for cement clinker firing. In addition, pozzolanic materials increase concrete's resistance to corrosive environments, reducing the risk of reinforcement corrosion and structural failure. With the global drive to reduce greenhouse gas emissions and rational use of natural resources, the introduction of alternative binders in concrete becomes an important step towards a more environmentally friendly and durable construction industry.

The paper [4] analyzes the use of natural pozzolans such as zeolite and pumcite as a partial replacement of cement in water permeable concrete mixes. The mechanical and hydraulic properties of concrete at different cement replacement percentages (from 0% to 20%) and the effect of plasticizer addition are investigated.

Our study also focused on the development of formulations aimed at reducing cement consumption, a critical step towards more sustainable and cost-effective building materials. Cement production is one of the largest sources of carbon dioxide emissions, making its reduction an important objective in addressing environmental concerns. Reducing cement consumption not only reduces the carbon footprint but also helps to optimize resource utilization without compromising material performance.

To achieve this goal, we investigated the possibility of partially replacing cement with local materials such as ground tuff and fly ash from CHP-2. These materials are by-products or natural resources, which makes them advantageous both economically and environmentally.

This approach is in line with global trends towards sustainable construction and resource management. By using alternative binders, I aim to create lightweight and durable concrete with a lower environmental impact. Such compositions not only advance the science of building materials, but also promote more sustainable construction methods that benefit both industry and the environment.

Several studies have investigated the possibility of using volcanic tuff as a partial replacement for cement in concrete to improve sustainability and reduce environmental impact. For example, studies [5] show the content of natural volcanic tuff in concrete mixtures with replacement levels ranging from 10% to 50%. These studies demonstrate improvements in mechanical properties, such as a 35.6 % increase in flexural strength and a 56.5 % increase in durability by reducing water permeability. The pozzolanic activity of volcanic tuff contributes to the densification of the concrete microstructure (Figure 1), resulting in the following benefits.

Thus, the high pozzolanic activity of natural pozzolanic tuff powder in cement composites is due to the combined action of nucleation, filling and pozzolanic reactions, with the filling and nucleation effects being the dominant factors.

Another study [6] investigated lightweight structural concrete with volcanic tuff and fly ash. This study emphasizes the economic and environmental advantages of using such materials in achieving desired rheological and mechanical properties. In particular, it showed promising applications in self-compacting concrete.

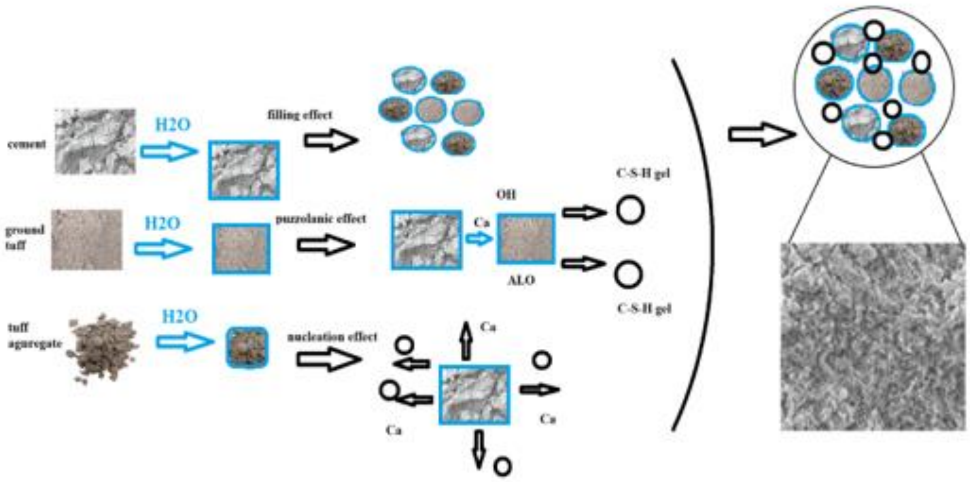

Figure 1 - Improvement of concrete microstructure with volcanic tuff particles and visualization of pozzolanic effect [6]

These findings suggest that volcanic tuff can make a significant contribution to sustainable construction by reducing cement consumption and carbon emissions without compromising concrete performance.

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These findings suggest that volcanic tuff can make a significant contribution to sustainable construction by reducing cement consumption and carbon emissions without compromising concrete performance.

Studies show that the use of fly ash in concrete mixtures not only improves strength properties but also significantly reduces cement consumption. Fly ash has pozzolanic activity with respect to cement, which promotes the formation of additional calcium silicate hydrate during concrete curing, improving its durability and strength in the long term.

One of the key benefits is the reduction of environmental impact as fly ash replaces part of the cement, which also contributes to the reduction of CO_2 emissions associated with cement production. Specifically, studies have shown that replacing 15-25% of cement with fly ash can significantly reduce carbon dioxide emissions without significantly compromising the mechanical properties of concrete [8]. In addition, fly ash helps to reduce water consumption and thermal effects during the hydration process, which is particularly important for the development of sustainable and environmentally friendly building materials [9].

Thus, the use of fly ash in concrete mixtures is an effective way to create more sustainable and environmentally friendly building materials while reducing cement costs.

Puzzolan is a material composed of silicates, aluminosilicates or a combination of both. It does not harden on its own when mixed with water. However, when finely ground and in the presence of water at normal temperature, it reacts with calcium hydroxide ($Ca(OH)_2$) to form calcium hydrosilicates and hydroaluminates. These compounds impart strength to the hardened material, similar to the hardening processes of hydraulic binders.

Volcanic tuff is often characterized by a high content of pozzolanic components such as silica and aluminosilicates, making it a valuable raw material for the production of building materials. Due to its high pozzolanic activity, tuff is able to interact effectively with calcium hydroxide in the presence of water to form strong calcium hydrosilicates and hydroaluminates. This property allows it to be used as a natural additive to cements and concretes, improving their strength characteristics, durability and resistance to aggressive media.

Pozzolans are mainly composed of reactive silica (SiO_2) and alumina (Al_2O_3), with smaller amounts of iron oxide (Fe_2O_3) and other oxides. The mass fraction of reactive silica (SiO_2) should be at least 25%.

Fly ash is produced by electrostatic or mechanical precipitation of fine particles from the flue gases from the combustion of pulverized coal or oil shale. The chemical composition of fly ash can be acidic, with high SiO_2 content, or basic, with high CaO content. The acidic ash exhibits pozzolanic properties, while the basic ash can also exhibit hydraulic properties.

The alkali oxide (R_2O) content, converted as Na_2O, should not exceed 2.0% by weight, and the MgO content should not be more than 5%. The loss on ignition of fly ash shall not exceed 5.0%, although fly ash with a loss on ignition of up to 7.0% is acceptable. When fly ash with a loss on ignition above 5.0% but up to 7.0% is used in cement compositions, a maximum loss on ignition of 7% shall be specified on the packaging and in the accompanying documentation. The uniformity of volume change (expansion) of cement with fly ash additives should not exceed 10 mm [10].

The article is devoted to the study of the effect of basaltic pozzolan addition on the strength and durability of concrete. Different levels of cement replacement and their effect on concrete characteristics are considered [11].

Experimental part

Materials. In this paper, cement, ground volcanic tuff, fly ash, tuff sand, tuff crushed stone and polypropylene fiber (PPF) were used as the main components of concrete mixtures. Each of these materials has specific characteristics that affect the properties of the resulting concrete.

Ordinary Portland cement (CEM I 42.5N) was used in the study, produced by HeidelbergCement. Its partial replacement with alternative materials aims to reduce the carbon footprint and improve the durability of the concrete.

Ground volcanic tuff is a natural pozzolan capable of reacting with calcium hydroxide to form additional calcium silicate hydrates, which helps to increase the density of the cement stone. Volcanic tuff used in this study was obtained from a natural deposit located in the Chundzha region (Almaty oblast, Kazakhstan). The material was preliminarily dried, crushed, and sieved to obtain a powder suitable for use as a mineral additive. Fly ash was sourced from Thermal Power Plant No. 2 (TPP-2) in Almaty.

Fly ash, which is a waste product of coal combustion at thermal power plants, also exhibits pozzolanic properties, improving the structure of concrete and reducing its permeability.

Tuff sand and tuff crushed stone were used as aggregates, which have a porous structure and relatively low density, which can affect the strength properties of concrete. The use of such aggregates makes the concrete lighter and improves its thermal resistance.

In addition, polypropylene fiber (PPF) was introduced into the composition to increase the crack resistance of concrete and prevent shrinkage deformations in the early stages of curing. Polypropylene fibers with a length of 12 mm were used as a reinforcing additive for foam concrete mixtures. The fibers were supplied by LLP "Damu – Khimiya" (Kazakhstan) and were incorporated to enhance the tensile strength, reduce shrinkage cracking, and improve the overall durability of the foam concrete.

The combined use of these materials is aimed at creating a more environmentally friendly and durable concrete by reducing the cement content and improving the performance of the material.

Methods

Elemental analysis of volcanic tuff and fly ash composition. Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS) analyses were conducted using a JEOL NeoScope JCM-7000 microscope (JEOL Ltd., Japan) to study the microstructure and elemental composition of the hardened cement matrix. The procedures followed standard protocols for microstructural analysis of cementitious materials, as described in [12]. This state-of-the-art instrument allows for high-resolution imaging and accurate determination of the elemental composition of the materials, making it possible to identify key components in the samples. Using energy dispersive X-ray spectroscopy (EDS), the SEM provided detailed information on the chemical composition of the pellets, including the distribution of silica, alumina and other oxides. The resulting images revealed microstructural features of the granules such as porosity, particle size, and surface morphology. These characteristics are crucial to understanding the pozzolanic activity of the material and its suitability as an additive in cement and concrete. Through this analysis, the reactivity and potential efficacy of volcanic tuff and ash in various applications can be accurately assessed.

The elemental and microstructural analysis performed with the JEOL NeoScope SEM is essential for both scientific research and practical applications. Understanding the composition and structure of volcanic tuffs and ashes helps researchers evaluate their potential as additional cementitious materials. High pozzolanic activity, indicated by the significant presence of reactive silica and alumina, enhances the strength and durability of concrete when these materials are used as additives. SEM images provide insight into how these granules interact in the matrix, affecting factors such as hydration and bonding. These data are not only important for improving material performance, but also contribute to sustainable construction by encouraging the use of natural and industrial by-products. The analysis thus contributes to the development of innovative, environmentally friendly building materials with improved properties.

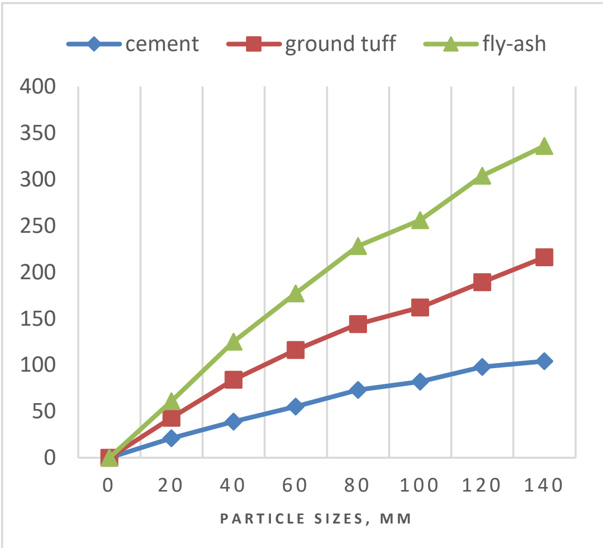

Figure 2 - Granulometric composition of natural volcanic tuff and Portland cement particles

Determination of the fineness of grinding of volcanic tuff and fly ash. The fineness of grinding of volcanic tuff and fly ash of TPP-2 was determined by the requirements of the standard [13], which sets forth the standard methodology for assessing the fineness of mineral powders. The particle size distribution of natural volcanic tuff and Portland cement, adapted from [14], is shown in Figure 2.

This test is of great importance for assessing the quality of materials used in cement and concrete production, since particle size significantly affects pozzolanic activity, hydration rate and general mechanical properties. The procedure involves determining the residual material on a standard sieve with 45-micron mesh openings. This allows consistent comparison of particle sizes in different samples and ensures that the material meets industry requirements.

The test begins with sample preparation, which is thoroughly dried to remove moisture that could affect the results. A certain mass of material, usually 50 grams, is weighed and placed in a sieve with a mesh size of 45 microns (Figure 3). The sieve is placed on a vibrating bench that is run for 15 minutes to ensure uniform and complete sieving. After sieving, the residue on the sieve is collected and weighed. The percentage of residue is calculated as a fraction of the original mass.

Figure 3 - Determination of grinding fineness of volcanic tuff

The results are then compared with the limit values set by the standard [13]. As a rule, the material is considered fine enough if no more than 10% remains on the sieve. This standard guarantees the high reactivity of the material and its suitability for use in pozzolanic or hydraulic systems. By following this methodology, researchers and manufacturers can guarantee the quality and efficiency of ground volcanic tuff and fly ash in various building materials.

Determination of grinding fineness by specific surface using Le Chatelier's device. The specific surface of ground volcanic tuff and fly ash was determined using the Le Chatelier device (Figure 4) by the standard [13]. This method allows for evaluation of the fineness of grinding by measuring the specific surface of the material (m²/kg), which is the most important parameter affecting the reactivity, strength set and durability of materials used in cement and concrete. The Le Chatelier method is based on the principle of air permeability, where the time required for air to pass through a compacted specimen serves as an indirect measure of particle size distribution.

To begin the test, the Le Chatelier instrument is calibrated, and the sample is dried to remove moisture. A specified mass of finely ground material, usually 2-5 grams, is weighed and placed in the cell of the instrument. The sample is uniformly compacted using a standard plunger to ensure a consistent packing density. The apparatus is then connected to an air permeation system, and a constant flow of air is passed through the sample.

The time required for a certain volume of air to pass through the sample is recorded. This time is used to calculate the specific surface area of the material using the calibration curve supplied with the instrument. The specific surface area is expressed in square meters per kilogram (m²/kg).

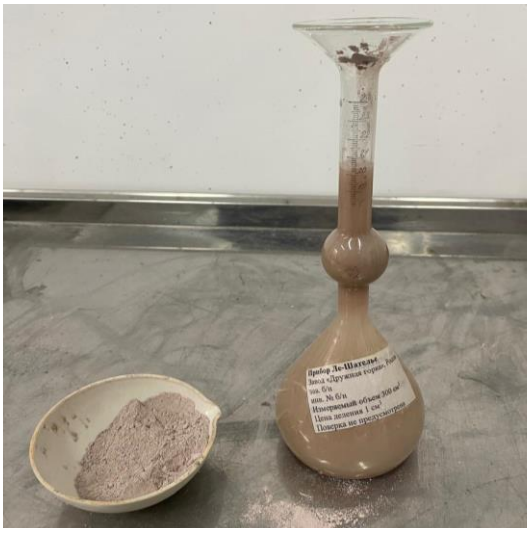

Figure 4 - Determination of specific surface using Le Chatelier's device

The results obtained are compared with the required values for the intended application. For pozzolanic and supplementary cementitious materials, a higher specific surface area usually indicates better reactivity and efficiency in the cement matrix. This method provides a reliable and reproducible way to evaluate the fineness of volcanic tuff and fly ash, ensuring that they meet industry standards for use in building materials.

Selection of lightweight concrete composition using ground tuff and fly ash. To evaluate the potential of volcanic tuff as a partial replacement for cement, a series of concrete mixtures were designed and prepared (Table 1). The mixes included a control mix (27PPF) and variants in which cement was replaced with ground tuff in proportions of 10%, 15%, 20%, 25%, 30% and 35%. In each mix, the ratio of tuff sand, tuff aggregate and polypropylene fibers (PPF) was kept constant at 1.5% by volume to ensure homogeneity of the other components. The water-to-cement (W/C) ratio was adjusted to 0.5 for the control and 10% replacement variants, while for higher percentages of tuff replacement (15% and above), the W/C ratio was increased to 0.6 to account for the altered workability. These adjustments ensured that the mixtures met the practical requirements for casting and testing.

The prepared concrete specimens were subjected to a rigorous testing program to analyze the effect of replacing cement with ground tuff on basic properties such as compressive strength and durability. The objective was to determine the optimum level of replacement that maintains or improves the mechanical performance of the concrete while reducing the cement requirement. This approach not only aims to improve the sustainability of concrete production but also explores the potential of volcanic tuff as a viable supplemental cementitious material to promote resource conservation and environmental improvement.

Table 1 - Selection of formulations with ground tuff as a substitute for binder

No.	Cement, g	Ground tuff, g	Tuff sand, g	Tuff crushed stone, g	Fiber quantity, g	W/C
27PPF	400	-	640	820	6	0.5
27PPF (10%)	360	40	640	820	6	0.5
27PPF (15%)	340	60	640	820	6	0.6
27PPF (20%)	320	80	640	820	6	0.6
27PPF (25%)	300	100	640	820	6	0.6
27PPF (30%)	280	120	640	820	6	0.6
27PPF (35%)	260	140	640	820	6	0.6

Table 2 - Selection of compositions with ash from CHPP 2 as a replacement for the binding agent

No.	Cement, g	Fly-ash, g	Tuff sand, g	Tuff crushed stone, g	Fibres Fibre quantity, g	W/C
27PPF	400	-	640	820	6	0.5
27PPF (10%)	360	40	640	820	6	0.5
27PPF (15%)	340	60	640	820	6	0.6
27PPF (20%)	320	80	640	820	6	0.6
27PPF (25%)	300	100	640	820	6	0.6
27PPF (30%)	280	120	640	820	6	0.6
27PPF (35%)	260	140	640	820	6	0.6

In addition to investigating volcanic tuff as a partial cement replacement, concrete samples were also prepared using CHP-2 fly ash as a binder (Table 2).

For uniformity, the same mix proportions were followed, with cement being partially replaced by fly ash in percentages of 10%, 15%, 20%, 25%, 30% and 35%. In these mixtures, the same aggregate composition, including tuff sand and tuff aggregate, was maintained, and polypropylene fibers (PPF) were added at a dosage of 1.5% by volume. We can observe the manufactured specimens in Figure 5. The water-to-cement ratio (W/C) was also adjusted, kept at 0.5 for the control mix and the mix with 10% ash, and increased to 0.6 for mixes with 15% and above to ensure sufficient workability during casting.

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Specimens were prepared to analyze and compare the performance of concrete with volcanic tuff and fly ash as a partial replacement for cement. The testing of properties such as compressive strength and durability is aimed at determining the most effective use of these alternative materials in concrete production.

Figure 5 - Concrete samples with CHPP 2 ash as a partial replacement of binder

The use of fly ash, a by-product of thermal power plants, is in line with the Sustainable Development Goals by utilising industrial waste and potentially improving concrete properties. This parallel study allows a comprehensive evaluation of the environmental and mechanical benefits of these supplementary cementitious materials.

Results and Discussion

1) Chemical composition. Volcanic tuff is characterized by a high SiO content of 69.26 %, determined by X-ray spectral microanalysis (EDS) on an electron probe microanalyzer JCTXA-733. We can observe the percentage of chemical composition in Table 3. This significant proportion of silica indicates a high silicate content, which corresponds to the classification of pozzolans according to standard [10]. According to this standard, the minimum silica content requirement for materials classified as pozzolans is 25%. The exceptionally high silica content in volcanic tuff not only meets but also significantly exceeds this threshold, which allows the finely ground tuff to be classified as pozzolanic materials.

Table 3 - Chemical composition of volcanic tuff

Compound, % by mass								
SiO_2	Al_2O_3	K_2O	Na_2O	CaO	FeO	MgO	TiO_2	MnO
69.26	16.04	6.24	3.44	2.46	1.57	0.57	0.14	0.28

Figure 6 is an energy dispersive X-ray spectrum (EDS) obtained using a JEOL scanning electron microscope. The spectrum shows the presence of the main elements that make up the material, including aluminum (Al), silicon (Si), calcium (Ca), iron (Fe), magnesium (Mg), potassium (K), titanium (Ti), and oxygen (O), confirming its mineral nature. The most intense peaks correspond to AlKα and

SiKα, indicating a high content of aluminosilicate phases characteristic of fly ash. The results confirm the chemical composition of the material and its potential as a pozzolanic admixture in concrete.

These data confirm the possibility of using finely ground volcanic tuff as a partial replacement for traditional binders in cement systems. The pozzolanic properties of the material, due to its high silica content, increase its ability to react with calcium hydroxide during the hydration process, improving the durability and mechanical properties of concrete.

This application is consistent with sustainable construction practices, as it reduces the need for conventional Portland cement, which produces significant CO_2 emissions. The use of volcanic tuff in this context represents an environmentally friendly alternative that allows the use of natural resources while maintaining the quality standards required for modern construction.

In the article [15], chemical parameters of fly ash obtained at Almaty CHPP-2 were determined, including the content of silicon (SiO2), titanium (TiO2), aluminum (Al2O3), iron (Fe2O3), calcium (CaO), magnesium (MgO), sodium (Na2O), potassium (K2O) oxides and other impurities. The results show that the highest content in the ash is silicon oxide (65.0-65.9%), which is typical for materials used in construction, such as cement. Variations in the content of other oxides were also assessed, which allows for a better understanding of the properties and possible applications of this ash in various industries, such as in the production of building materials or in improving soil quality.

Figure 7 shows us fly ash particles captured on an electronic scanning microscope.

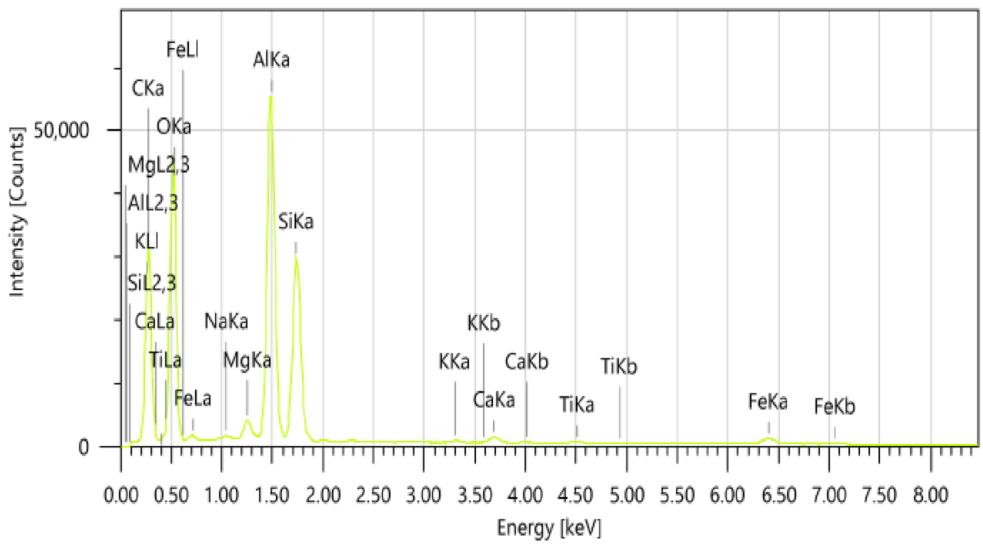

Figure 6 – X-ray energy dispersion analysis (EDS) of fly ash from CHPP 2

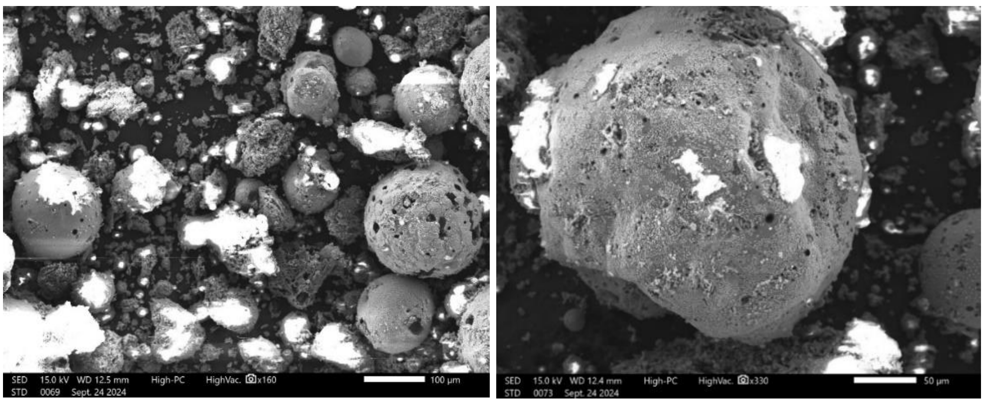

Figure 7 – Scanning electron microscope images of ash from CHPP 2

2) The fineness of grinding of crushed tuff and fly ash was determined in accordance standard [16], which evaluates the material retained on a sieve with a mesh size of 0.08 mm. For both tuff and fly ash, the fineness values were slightly higher than for cement, indicating a somewhat coarser particle distribution. Despite this, the obtained values are in the acceptable range for use as additional cement materials. The grinding process achieved a sufficient reduction in particle size, which ensures good compatibility with cement for partial replacement. The residue on a 0.08 sieve for ground tuff was on average 8.5%, while for ash, this figure was 11.5%. At the same time, the norm for standard cement is no more than 10%.

The slightly higher fineness values for tuff and fly ash reflect their natural characteristics and production processes. However, these results indicate that both materials are reactive enough to contribute to the cement matrix and participate effectively in hydration reactions. These characteristics make them suitable for use in concrete mixtures where partial replacement of cement is required, offering potential environmental benefits and reducing the carbon footprint. In addition, their fineness allows them to mix well with other components of the mixture, while maintaining the required workability and strength development properties of concrete.

The article [17] discusses how the degree of dispersion of components such as lime and slag affects the physical and mechanical properties of autoclaved materials. Reducing the grain size of the binder components helps to improve these properties, but if the grinding is too fine, the particles may stick together, which leads to the opposite effect.

3) The specific surface area of ground tuff and fly ash was determined by GOST 310.2-76. The obtained values were within the standard range for cement. The specific surface area of ground tuff was 241 m^2/kg, which is slightly lower than the typical value for ordinary Portland cement. This result indicates good fineness of tuff, which makes it suitable for use as a partial replacement for cement in concrete. A higher specific surface area increases the reactivity of the material, positively affecting the cementitious properties of the mixture.

Several studies have examined the effect of the specific surface area of ash on the properties of building materials. It has been established that an increase in the dispersion of ash, for example, from hydrodecarbonization, increases its pozzolanic activity, which improves the mechanical properties of concrete and the durability of materials. Studies show that optimizing the degree of grinding of ash, with a specific surface area above 250 m^2/kg, helps to increase the strength and efficiency of its use in cement and concrete mixtures [[18], [19], [20]].

Similarly, the specific surface area of fly ash was determined to be 229 m^2/kg, which is also within the acceptable range. This value confirms the potential of fly ash to be used as a supplementary cementitious material. Sufficient fineness ensures that the material can combine well with cement and contribute to the compaction of the microstructure. Both materials show promise in reducing cement consumption while maintaining or improving the performance of concrete.

4) Strength properties were also determined according to standards, and cube specimens were prepared and tested using a hydraulic press. The specimens included mixtures with ground tuff and fly ash as a partial replacement for cement. The cubes were prepared according to standard procedures to ensure consistency and reliability of the results. The tests were conducted to evaluate the compressive strength of these modified mixtures at different curing times. The inclusion of ground tuff and fly ash was aimed at assessing their effect on the mechanical properties of concrete. The results obtained on the hydraulic press provided valuable information on the feasibility of using these materials as additional cementing components while maintaining or increasing the overall strength of concrete.

The effect of fly ash and pozzolan additives on the strength of concrete has been studied in various studies. In one of them, when replacing up to 40% of cement with ash additives, the strength of concrete after 28 days remained close to the control, and after 60 days it was almost equal to the strength of concrete without the additive. In another study, the use of fly ash and microsilica as mineral additives in concrete showed an increase in compressive strength compared to the control composition. Also, in a study of the effect of pozzolanic additives such as fly ash and metakaolin on the reaction of alkali with silica, a decrease in the expansion of concrete was observed, indicating a positive effect of these additives on strength characteristics. Finally, a study of the effect of ash residues from the processing of municipal solid waste on the properties of concrete showed that concrete with an ash content of 10-20% has the highest compressive strength, reaching about 60 MPa [[21], [22], [23], [24]].

Table 4 – Strength and average density indicators of lightweight concrete using ground tuff and ash as a partial replacement of the binder

No.	Ash or tuff content, %	Average density, kg/m^3	Compressive strength, MPa
27PPF	-	1925.5	40.1
27PPF Tuff	10	1927.0	40.7
27PPF Tuff	15	1928.5	39.6
27PPF Tuff	20	1924.6	37.7
27PPF Tuff	25	1926.8	32.1
27PPF Tuff	30	1920.2	28.3
27PPF Tuff	35	1926.3	27.9
27PPF Fly-ash	10	1924.6	41.6
27PPF Fly-ash	15	1919.5	40.4
27PPF Fly-ash	20	1914.8	38.5
27PPF Fly-ash	25	1913.6	35.8
27PPF Fly-ash	30	1914.5	30.7
27PPF Fly-ash	35	1910.4	29.1

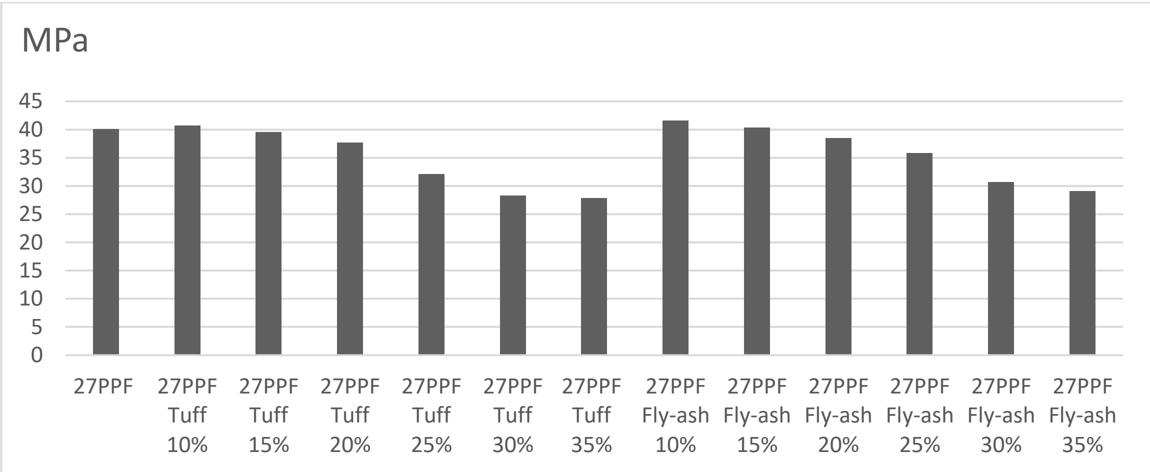

Figure 8 – Graph of the dependence of the strength indicator on the amount of ground tuff and ash as a partial replacement for the binder

The data demonstrate the effect of replacing cement with ground tuff or fly ash on the average density and compressive strength of 27PPF concrete mixtures. For both admixtures, the compressive strength generally decreases with increasing replacement percentage. This trend is more pronounced at higher substitution levels, indicating that excessive cement substitution may weaken the concrete matrix, probably due to a decrease in the binder properties of the mixture, as can be seen in Table 4.

In the case of ground tuff, the compressive strength remains relatively stable up to 15% replacement, after which a slight decrease is observed. After this point, the strength decrease becomes significant, decreasing to 37.7 MPa at 20% and further to 27.9 MPa at 35%. Similarly, the density of the mixtures fluctuates slightly but remains within a narrow range, indicating that the influence of ground tuff on the bulk properties of the material is minimal until higher substitution levels. In Figure 8, we can see the strength as a function of the percentage of ground tuff and ash.

A similar trend is observed for fly ash mixtures, although the compressive strength values are slightly higher compared to tuff at equivalent substitution levels. At 10% ash replacement, the compressive strength increases to 41.6 MPa, indicating the potential of ash to improve early performance. However, when the substitution level reaches 30-35%, the strength drops below 31 MPa, similar to tuff mixtures.

Overall, these results indicate that moderate replacement (10-15%) of ground tuff or fly ash can maintain acceptable strength and density, while higher replacement levels degrade mechanical performance. Fly ash appears to provide superior performance compared to tuff, especially at lower substitution rates.

Conclusions

1. The results indicate that partial replacement of cement with ground volcanic tuff and fly ash at moderate levels (10–15%) maintains compressive strength and density within acceptable limits, demonstrating the potential of these materials as supplementary cementitious components. Ground tuff shows relatively stable performance with a slight decrease in strength and density, while fly ash exhibits an early strength gain due to its pozzolanic activity, which enhances matrix compaction during the initial hardening phase.

2. At higher substitution rates (20% and above), both materials cause a significant reduction in compressive strength, more pronounced for volcanic tuff, where strength drops below 30 MPa at 35% replacement, limiting its suitability for high-performance concrete applications. Fly ash performs slightly better under similar conditions but still leads to considerable strength loss, emphasizing the need for careful optimization of replacement levels to ensure structural integrity.

3. The chemical composition of volcanic tuff, with a high silica content (69.26% SiO_2), confirms its pozzolanic nature and suitability for partial cement replacement. This contributes to the environmental benefits of reducing cement consumption and associated carbon emissions in concrete production.

4. Although the particle size distribution of volcanic tuff and fly ash is coarser compared to conventional cement, their fineness remains within acceptable ranges that allow effective participation in hydration reactions. This supports their positive effect on the mechanical properties of the resulting concrete mixtures.

5. Strength testing confirms that cement replacement up to 15% with either ground volcanic tuff or fly ash does not compromise concrete performance and may slightly improve early strength in the case of fly ash. These findings highlight the potential of both materials to serve as sustainable alternatives in cementitious systems without significant loss of mechanical properties.

Conflicts of interest. On behalf of all the authors, the corresponding author declares that there is no conflict of interest.

CRediT author statement: **R. Nurlybayev, M. Zhuginissov and E. Kuldeyev:** Conceptualization; **M. Zhuginissov and Y. Khamza:** Methodology; **Y. Khamza, Y. Orynbekov and A. Iskakov:** Software; **R. Nurlybayev, M. Zhuginissov and Y. Orynbekov:** Formal analysis; **M. Zhuginissov and Y. Khamza:** Writing—original draft preparation; **E. Kuldeyev and R. Nurlybayev:** Visualization, Project administration, Funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Жеңіл конструкциялық бетон құрамында пуццоландық қоспалар ретінде күлді және ұнтақталған туфты қолдану

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ТҮЙІНДЕМЕ
Бұл жұмыста цементті ұшпа күлмен және ұнтақталған жанартаулық туфпен (туф-құрылыс материалы ретінде қолданылатын тау жынысы) ішінара ауыстырудың бетонның физика-механикалық қасиеттеріне әсері зерттеледі. Негізгі назар материалдардың әртүрлі құрамындағы орташа тығыздық пен қысу беріктігінің өзгеруіне (10%-дан 35%-ға дейін) аударылады. Зерттелетін қоспасыз бетон құрамының (27PPPF) орташа тығыздығы 1925,5 кг/м³ және қысымға беріктігі 40,1 МПа. Нәтижелер ұшпа күлді қосқанда алдымен бетонның беріктігі артып, цементті 10% ауыстырғанда максималды мәнге 41,6 МПа жетеді, содан кейін 35% ауыстырғанда 29,1 МПа дейін төмендейтінін көрсетеді. Осыған ұқсас үрдіс туфты енгізген кезде байқалады, бірақ беріктік шыңына (40,7 МПа) 10% ауыстыру кезінде де жетеді, содан кейін беріктік 35% кезінде 27,9 МПа дейін біртіндеп төмендейді. Үлгілердің орташа тығыздығы шамалы өзгереді, 1910,4-1928,5 кг/м³ аралығында болады, бұл бетонның тығыз құрылымының сақталғанын көрсетеді. Осылайша, бетон құрамындағы ұшпа күл мен туфтың оңтайлы мөлшері 10-15% құрайды, өйткені бұл көрсеткіштер ең жақсы механикалық сипаттамалар береді. Ауыстырылатын заттардың жоғары дозалары цемент тасының жұқаруы мен байланыстырушы қасиеттерінің болмауына байланысты беріктіктің төмендеуіне әкеледі. Бұл зерттеу бетонның экологиялық тазалығы мен тұрақтылығын арттыру үшін тиімді пуццоландық қоспалар ретінде ұшпа күлді және жанартау туфын пайдалану мүмкіндігін растайды.

Түйін сөздер: ұшпа күл, пуццоландық әсер, туф, байланыстырғыш, жеңіл конструкциялық бетон.

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Использование летучей золы и молотого туфа в качестве пуццолановых добавок в составе легкого конструкционного бетона

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АННОТАЦИЯ
В данной статье исследуется влияние частичной замены цемента летучей золой и молотым вулканическим туфом на физические и механические свойства бетона. Основное внимание уделяется изменениям средней плотности и прочности на сжатие при различных содержаниях заменяющих материалов (от 10% до 35%). Исследуемый бетонный состав (27PPF) без добавок имеет среднюю плотность 1925,5 кг/м³ и прочность на сжатие 40,1 МПа. Результаты показывают, что при добавлении золы уноса прочность бетона сначала увеличивается, достигая максимального значения 41,6 МПа при 10% замещения цемента, после чего снижается до 29,1 МПа при 35% замены. Аналогичная тенденция наблюдается и при введении туфа, однако пик прочности (40,7 МПа) достигается также при 10% замены, после чего прочность постепенно уменьшается до 27,9 МПа при 35%. Средняя плотность образцов изменяется незначительно, находясь в диапазоне 1910,4–1928,5 кг/м³, что свидетельствует о сохранении плотной структуры бетона. Таким образом, оптимальное

содержание летучей золы и туфа в составе бетона составляет 10–15%, поскольку при этих значениях обеспечиваются наилучшие механические характеристики. Более высокие дозировки заменителей приводят к снижению прочности, что объясняется разрежением цементного камня и недостатком вяжущих свойств. Данное исследование подтверждает возможность использования летучей золы и вулканического туфа в качестве эффективных пуццолановых добавок, способствующих повышению экологичности и устойчивости бетона.

Ключевые слова: летучая зола, пуццолановый эффект, туф, вяжущее вещество, легкий конструкционный бетон.

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