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Article

Physicochemical properties of silica fume and fly ash from Tau-Ken Temir LLP and Pavlodar CHP for potential use in self-compacting concrete

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Abstract. This article presents the results of a study on the structural and chemical properties of silica fume and fly ash from local plants, focusing on their potential as mineral additives in self-compacting concrete. Scanning electron microscopy (SEM) and X-ray fluorescence (XRF) analysis were used to investigate particle morphology, microstructure, and elemental composition. Silica fume was characterized by a high SiO_2 content (>75%), spherical particle morphology, and a smooth surface, which promotes the formation of a dense cement matrix. Fly ash exhibited a complex chemical composition dominated by SiO_2 and Al_2O_3 oxides, with spherical particles and surface roughness enhancing adhesion to the cement paste. The results demonstrated that the combined use of silica fume and fly ash has the potential to improve concrete workability, increase strength, reduce the water-cement ratio, and enhance durability due to microstructure densification. Partial cement replacement with these additives may not only optimize concrete performance but also reduce the environmental footprint of cement production. The findings highlight the efficiency of silica fume and fly ash as pozzolanic components for developing high-performance and sustainable self-compacting concrete.
Keywords: silica fume, fly ash, self-compacting concrete, mineral additives, pozzolanic materials, physical properties, microstructure, durability, sustainable construction.

1. Introduction

Cement production is accompanied by high CO_2 emissions, accounting for about 6-8% of global anthropogenic greenhouse gas emissions [1]. In addition, concrete mixtures often face problems of increased water consumption, shrinkage, porosity, and insufficient durability, especially under conditions of exposure to moisture and freeze-thaw [2]. The solution to these problems may be the partial replacement of cement with secondary cementitious materials such as silica fume and fly ash, which can improve the density, strength and rheological properties of cement compositions, as well as reduce the negative impact on the environment [3-4]. The combined application of cement, silica fume, and fly ash can significantly enhance the properties of self-compacting concrete while reducing cement consumption. Silica fume, due to its pozzolanic activity and tiny particle size, promotes and enhances the cohesion and strength of the concrete [5]. Fly ash, having the ability to fill pores and enhance the granulometric composition, promotes reduced water consumption in the mixture and increases its plasticity. By reducing cement consumption when using these mineral additives, CO_2 emissions are reduced during production, and general properties are improved, such as strength, shrinkage resistance, durability, and resistance to aggressive environments [6-7].

Numerous studies have shown that the application of silica fume and fly ash has a significant effect on the microstructure and properties of concrete. [9] found that the combined application of these additives enhances compressive and bending strength, as well as the microstructure of cement stone. At the same time, [10] confirmed similar results, noting a synergistic effect associated with increasing the packing density and pozzolanic activity of cement. Studies by [11] have shown that the application of fly ash and silica fume increases concrete's resistance to aggressive media, reducing permeability and improving its microstructure. Using machine learning techniques to analyze additive compositions [12] could accurately predict concrete strength, emphasizing optimizing their content.

In addition, the binary additive systems studied by [13] contribute to reducing the water-cement ratio, improving rheological properties, and increasing strength. The effect of fly ash on the micro- and macro-level properties of concrete was investigated by [14], who noted the uniform distribution of aggregate and reduction of microcracks.

[15] confirmed that using fly ash and silica fume increases the strength of concrete, especially in high-performance compositions. [16] emphasized the importance of these additives to increase the resistance of concrete to chloride penetration and its durability. These achievements are supported by the conclusions of [17], who demonstrated that using fly ash and silica fume additives in combination with reinforcement with plastic fibers enhances fiber adhesion to the matrix and reduces concrete shrinkage.

A study by [18] showed that various substrate hardening modes with fly ash and silica fume additives contribute to high strength, even during wet hardening. [19] confirmed that the combination of fly ash and silica fume reduces the sensitivity of concrete to hardening conditions and provides high strength even under unfavorable care conditions.

[20] studied the substrate's resistance to chloride corrosion. They showed that using fly ash and silica fume reduces the permeability of concrete, significantly increasing its durability. These results highlight the prospects of using pozzolan additives to modify concrete properties.

Based on the analysis of existing studies, it has been established that the properties of region-specific mineral additives, such as silica fume produced by Tau-Ken Temir LLP and fly ash from Pavlodar CHP, remain insufficiently studied. There is a lack of comprehensive data on their effect on the properties of self-compacting concrete, particularly regarding their influence on rheology, hydration processes, microstructure formation, and durability. Therefore, this research aims to fill this gap by investigating the effect of silica fume and fly ash on the properties of self-compacting concrete, including its mechanical characteristics, microstructure, and durability.

The primary purpose of the study is to develop approaches for partially replacing cement in concrete mixtures with these locally produced mineral additives to enhance both the environmental sustainability and performance of concrete. The objectives of the work include determining the optimal dosages of silica fume and fly ash, evaluating their influence on the rheological, strength, and durability properties of concrete, and analyzing microstructural changes associated with their use.

2. Methods

As a reactive pozzolanic additive, we used silica fume MKU-95, produced by «Tau-Ken Temir» LLP (Karaganda, Kazakhstan), corresponding to [21]. The physical and chemical properties of silica fume were assessed based on the provided technical documentation of «QAZAQ INNOTEC» LLP and verified using standard laboratory techniques where necessary.

To modify the cement mortar, we used fly ash obtained at the Pavlodar CHP. Fly ash is a by-product of coal combustion and has pozzolan properties, which allows it to be used as an active mineral additive in cement systems [22]. Its chemical composition includes a high percentage of silica fume (SiO_2), which enhances the durability and mechanical properties of the cement mortar [23].

For experimental analysis, samples of silica fume and fly ash were analyzed in their raw state without incorporating them into cement pastes or mortars using scanning electron microscopy (SEM) and X-ray fluorescence (XRF). To determine the elemental composition of the material, an energy-dispersive X-ray spectroscopy (EDS) analysis was conducted. The primary focus was to evaluate their physical, chemical, and microstructural properties. For SEM and XRF analysis, a small amount of finely ground silica fume and fly ash samples were prepared by sieving with a 200-mesh to obtain a powder with a particle size of 74 microns (μm) (i.e., 0.074 mm). The microstructure of the materials during SEM was analyzed using a Jeol JCM-7000 scanning electron microscope (Japan). The XRF analysis was carried out using a NEX CG II Series energy-dispersive X-ray fluorescence (EDXRF) spectrometer to determine the elemental composition of the material.

3. Results and Discussion

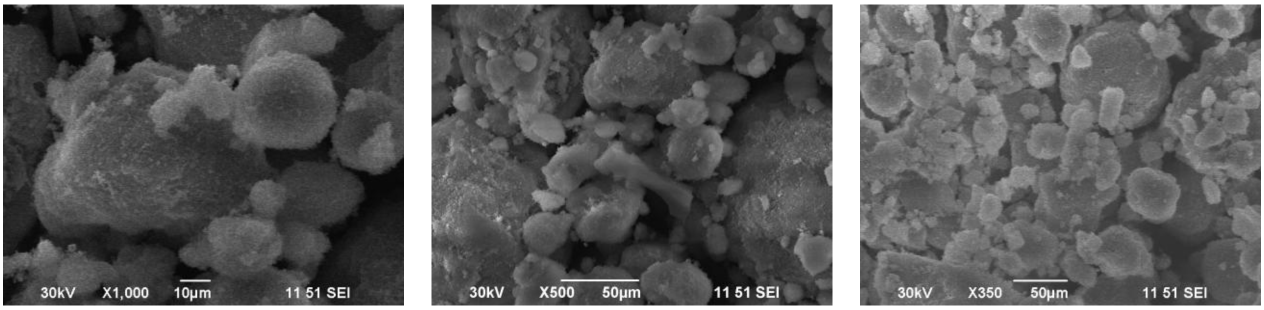
Table 1 presents the chemical composition of silica fume and fly ash.

Table 1 – Chemical composition of silica fume and fly ash

Material	Chemical composition element (ω, mass %)					
	C	O	Al	Si	Ca	Fe
Silica fume	-	48.77	-	51.23	-	-
Fly ash	18.4	48.3	7.6	18	5	6.4

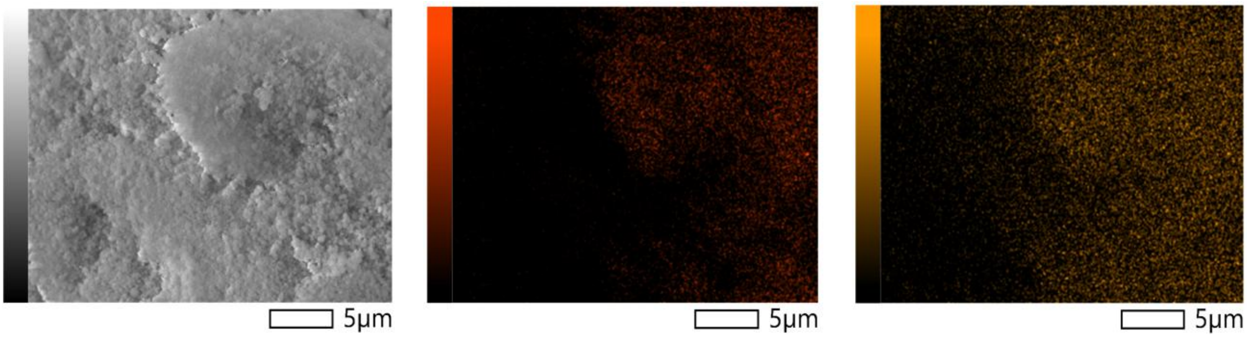
Table 1 shows that the chemical composition of silica fume consists primarily of silicon (Si) and oxygen (O), with mass fractions of 51.23% and 48.77%, respectively. This composition confirms the high purity of silica fume, which is mainly composed of silicon dioxide (SiO_2). The dominance of SiO_2 in silica fume is known to contribute to pozzolanic reactions in cementitious systems, enhancing concrete's overall durability and mechanical performance [24]. The chemical composition of fly ash contains multiple elements, including oxygen (48.3%), carbon (18.4%), silicon (18%), aluminum (7.6%), calcium (5%), and iron (6.4%). The presence of silicon and aluminum oxides indicates the pozzolanic nature of fly ash, which can react with calcium hydroxide in cement to form additional binding compounds, improving the long-term strength and durability of concrete [25]. The presence of carbon in fly ash suggests a certain level of unburned residue, which may influence its performance in cementitious mixtures [26].

Figures 1 and 2 below show the results of the SEM analysis of the silica fume.



a) Magnification of ×1000 b) Magnification of ×500 c) Magnification of ×350

Figure 1 – Microstructure of silica fume from SEM

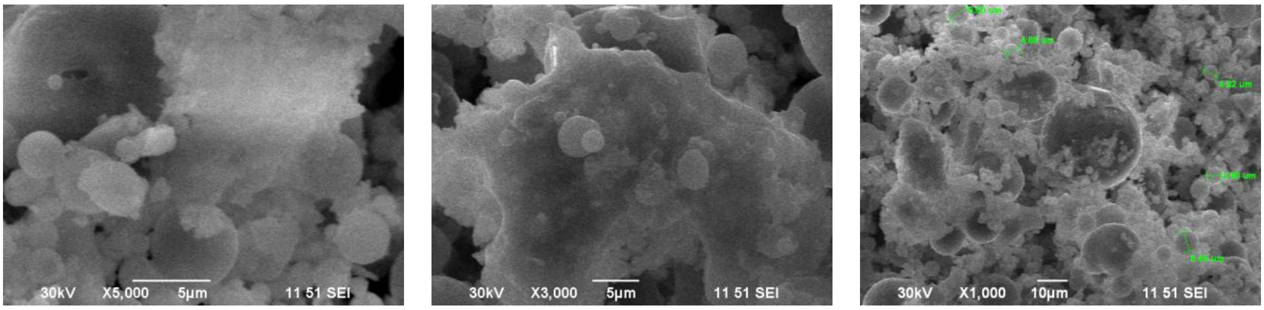


a) Image of silica fume particles b) Carbon (C) c) Aluminum (Al)

Figure 2 – Elemental mapping characterization of silica fume

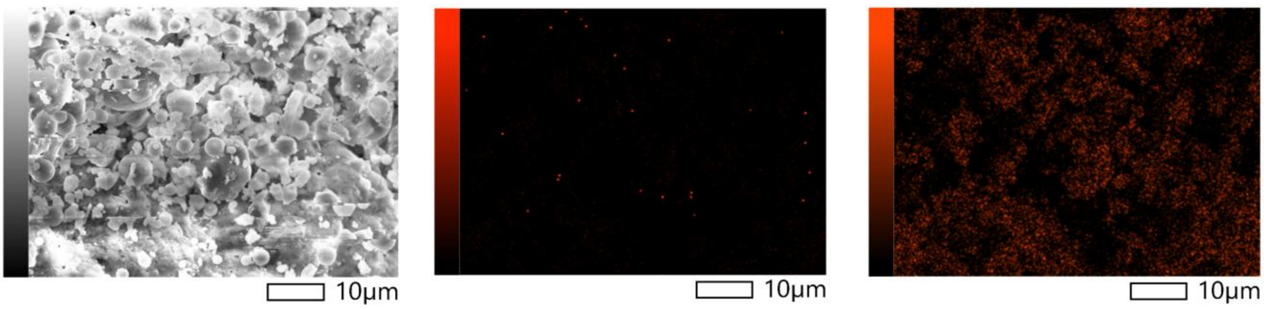
SEM images at ×1000 magnification (Figure 1a) demonstrate that silica fume particles are predominantly spherical, which is characteristic of materials formed during the condensation of silica oxide vapors. The particle size ranges from approximately 100 nm to 1–2 μm, indicating a high degree of dispersion and homogeneity. The images in Figures 1b and 1c at lower magnifications (×500 and ×350) reveal that individual particles tend to form agglomerates of various sizes due to interparticle forces, such as van der Waals interactions [27]. These agglomerates significantly exceed the size of individual particles, which should be considered when using silica fume in cementitious materials. Additional dispersion techniques may be required to ensure uniform particle distribution within the cement matrix. Higher magnification SEM images indicate that the surface of silica fume particles is smooth, with minimal defects. This smooth surface enhances particle adhesion to the cement matrix, which is expected to influence the mechanical properties of concrete composites positively. Elemental mapping performed on silica fume samples in Figure 2 confirms the uniform distribution of silicon and oxygen, with no visible impurities. The observed spherical morphology and fine particle size are consistent with the results reported by [28], who emphasized the role of silica fume in enhancing particle packing and reducing porosity in cement composites. The tendency for agglomeration was also noted in the work of [29], highlighting the need for proper dispersion methods when incorporating silica fume into concrete.

Figures 3 and 4 below show the results of the SEM analysis of the fly ash, with Figure 4 demonstrating the concentration of individual elements of fly ash at the micro level, where color gradients reflect the intensity of the presence of a particular element.

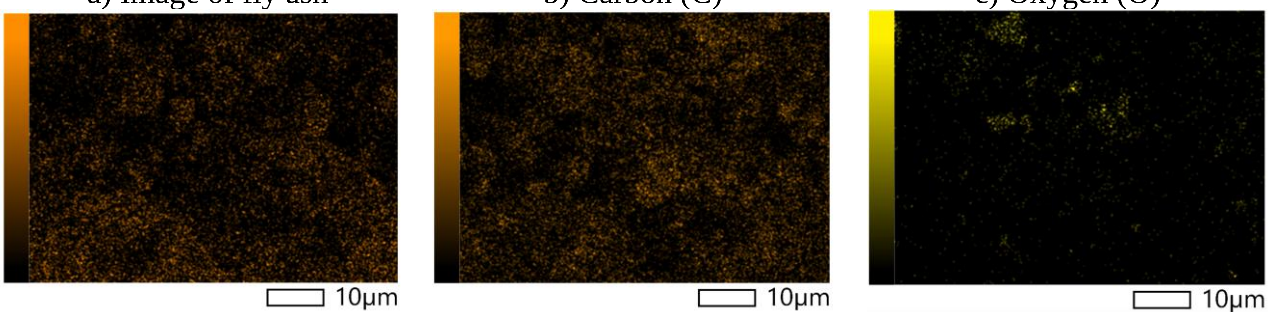


a) Magnification of ×5000 b) Magnification of ×3000 c) Magnification of ×1000

Figure 3 – Microstructure of fly ash from SEM



a) Image of fly ash b) Carbon (C) c) Oxygen (O)



d) Aluminum (Al) e) Silicon (Si) f) Calcium (Ca)

Figure 4 – Elemental mapping characterization of fly ash

Figure 3a, which demonstrates SEM images at ×5000 magnification, shows that fly ash particles predominantly have a spherical or near-spherical shape, which is typical for materials obtained from high-temperature combustion processes. The particle sizes vary from approximately 0.5 to 10 μm. Certain particles exhibit rough or irregular surfaces with small, embedded inclusions, indicative of the heterogeneous chemical nature of fly ash. These inclusions are likely associated with the presence of silica, alumina, and iron oxides, which may provide additional pozzolanic and binding properties. SEM image at ×1000 magnification (Figure 3c) shows that fly ash particles tend to form agglomerates, reaching sizes up to 20 μm. This agglomeration is attributed to physicochemical interactions between the particles. As with silica fume, the agglomeration may require additional dispersion measures during concrete preparation to ensure uniform particle distribution. The spherical shape of fly ash particles aligns with the findings of [30] and [31], who noted that this morphology improves workability and reduces water demand in concrete.

Figure 5 below shows the results of the XRF analysis of silica fume.

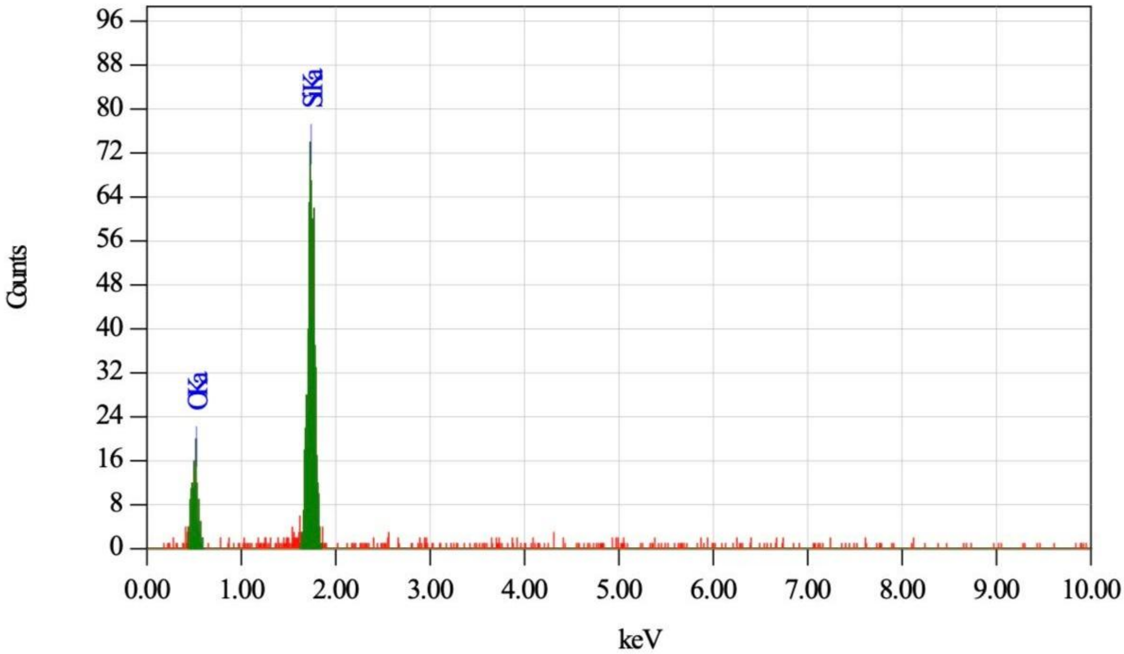


Figure 5 – XRF spectrum of silica fume

XRF analysis from Figure 5 confirmed that silica fume is characterized by a high content of silicon dioxide (SiO_2), which is consistent with its standard chemical composition. The XRF spectrum clearly shows a dominant SiKα peak, indicating that SiO_2 accounts for more than 75% of the material's composition, almost coinciding with [32]. The presence of the oxygen (OKα) peak further confirms that silica is in oxide form, which reflects the high purity of the material. The XRF data also revealed an absence or minimal presence of other elements, indicating a low level of impurities. This confirms the high quality of the silica fume, making it a particularly valuable pozzolanic material for high-performance concrete and cement composites. The high SiO_2 content is a key factor contributing to the pozzolanic activity of silica fume, enabling it to effectively interact with calcium hydroxide ($Ca(OH)_2$), which forms during cement hydration. This interaction results in the formation of additional calcium silicate hydrates (C-S-H), leading to the densification of the cement matrix and improvement in the mechanical strength and durability of concrete, as noted in [33]. Based on the XRF analysis, silica fume from the Tau-Ken Temir plant can be classified as a high-purity pozzolanic material suitable for applications in high-strength and self-compacting concrete, providing improved strength, reduced permeability, and enhanced durability.

Figure 6 below shows the results of the XRF analysis of fly ash.

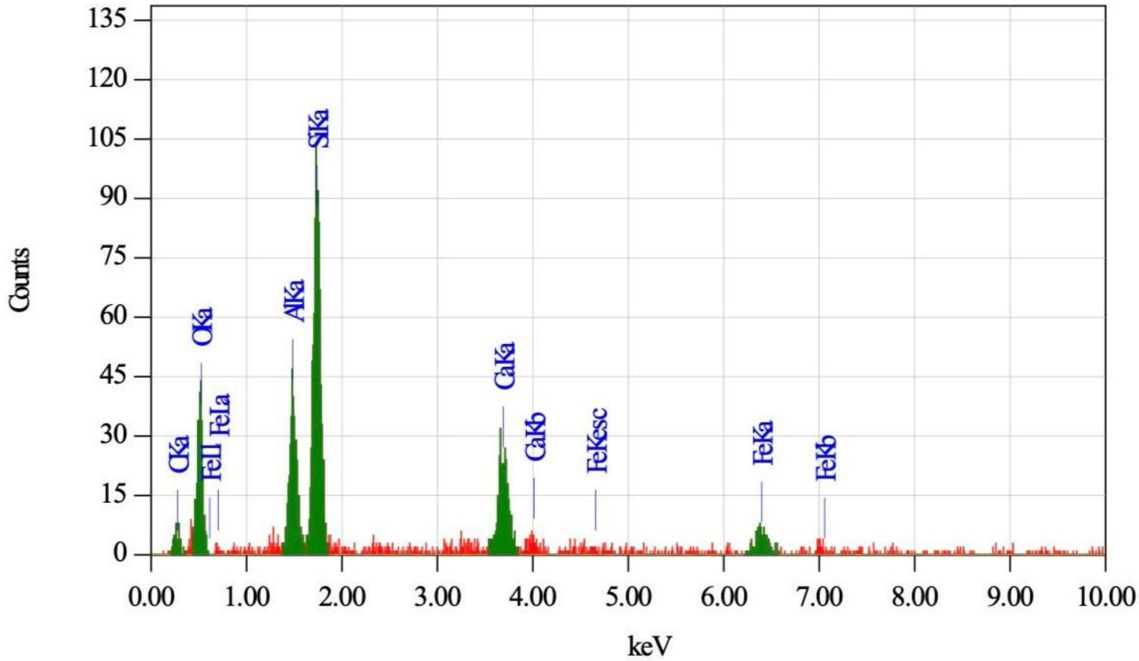


Figure 6 – XRF spectrum of fly ash

As shown in Figure 6 above, the XRF analysis of fly ash allowed for the determination of its elemental composition and confirmed the presence of the primary oxides responsible for the material's pozzolanic activity. The XRF spectrum reveals the presence of strong SiKα and AlKα peaks, indicating a high content of silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3), which form the primary matrix of fly ash. These oxides play a crucial role in the pozzolanic reactivity of the material, contributing to the strength and durability of cementitious composites [34]. The XRF spectrum also shows the presence of oxygen (OKα), confirming that the detected elements are present in oxide form. A calcium (CaKα) peak was recorded, indicating the presence of calcium oxide (CaO), which can participate in hydration reactions, improving the binding properties of fly ash. Iron peaks (FeKα and FeLα) were detected as well, corresponding to iron oxides (Fe_2O_3), which can influence the density, color, and certain physicochemical characteristics of the material. Additionally, trace amounts of potassium (Kα) and titanium (TiKα) were observed, indicating the complex chemical composition of fly ash. Although their concentrations are low, these elements may still indirectly affect the reactivity and performance of fly ash in cement systems. The XRF results demonstrate that fly ash is a multi-component oxide material with a high content of SiO_2 and Al_2O_3, confirming its suitability as a pozzolanic additive in cement and concrete. The presence of CaO and Fe_2O_3 suggests that the material can actively participate in cement hydration processes, while its pozzolanic properties contribute to improving strength and durability. These findings support the use of fly ash from the Pavlodar CHP to partially replace cement or use it as an active mineral additive in concrete, especially in alkaline environments. Earlier, in a study by [35], it was found that fly ash formed during the combustion of coal in thermal power plants contains significant amounts of silicon SiO_2 and aluminum Al_2O_3 oxides, which make up the bulk of its chemical composition. Besides, iron Fe_2O_3 and calcium CaO oxides are present in smaller amounts. Our results correspond to these data, confirming that the investigated fly ash has the acceptable properties required for pozzolan materials.

4. Conclusions

The study revealed key patterns in the behavior and properties of silica fume and fly ash as mineral additives for self-compacting concrete.

1. XRF analysis confirmed the high content of SiO_2 in silica fume (over 75%), which determines its pronounced pozzolanic activity. SEM images demonstrated that silica fume particles have a spherical shape, smooth surface, and a tendency to form agglomerates. The high dispersion

and purity of silica fume ensure its effective interaction with calcium hydroxide during hydration, which contributes to the densification of the cement matrix and an increase in strength and durability.

2. XRF analysis of fly ash showed that its composition is dominated by SiO_2 and Al_2O_3 oxides, which are responsible for its pozzolanic properties. SEM analysis confirmed that fly ash particles are predominantly spherical, with surface roughness and occasional agglomerates, characteristic of materials obtained from high-temperature coal combustion. The complex surface morphology of fly ash promotes adhesion to the cement matrix, improving the microstructure and mechanical properties of concrete.

3. The combined use of silica fume and fly ash allows for optimizing the composition of self-compacting concrete mixtures. Their simultaneous application contributes to reducing the water-cement ratio, increasing compressive and flexural strength, and enhancing resistance to aggressive environments. The synergy between the high dispersion of silica fume and the pozzolanic activity of fly ash leads to improved hydration processes and denser structure formation, which is especially important in the development of high-performance self-compacting concretes.

4. The results confirm the potential of silica fume and fly ash as effective mineral additives for the production of self-compacting concrete. Their partial replacement of cement not only improves the operational properties of concrete but also reduces its environmental impact, supporting the transition to more sustainable construction practices.

The findings of this study can serve as a basis for developing new high-performance concrete composites with improved strength, durability, and resistance to aggressive environments.

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