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Study of the suitability of industrial raw material resources as additives for Portland cement

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ABSTRACT
This research investigates the potential of utilizing industrial technogenic waste materials as hybrid mineral additives in the production of composite Portland cement (CPC), aiming to reduce clinker consumption and promote environmentally friendly construction practices. The studied materials include active ash and slag (AAS) from the Angren thermal power plant, microsilica (MS), and processed steelmaking wastes such as ladle slag (LS), furnace slag (FS), and recycled steel slag (RSS) from Uzmetkombinat JSC. The chemical, mineralogical, and mechanical properties of these materials were characterized in accordance with national and international standards. Compressive strength tests and lime absorption measurements evaluated their pozzolanic and hydraulic activities. Experimental results demonstrated that AAS exhibited the highest activity, capable of replacing up to 45% of clinker without compromising mechanical strength. When combined with less active components (MS, RSS, FS, and LS), hybrid additives showed synergistic effects. Among these, the AAS+MS blend had the most significant pozzolanic effect, evidenced by reduced calcium oxide (CaO) concentration in the surrounding liquid and lower solution alkalinity. The statistical validation using the Student's t-test confirmed the effectiveness of each additive, with t-values significantly exceeding the threshold required to classify them as active mineral additives. The findings support the development of "green" CPCs using hybrid additives derived from local industrial waste, offering a sustainable alternative to traditional raw materials. These formulations can significantly reduce carbon dioxide emissions, energy consumption, and natural resource depletion while maintaining cement performance, thus aligning with global trends toward low-clinker and low-carbon construction materials.

Keywords: industrial waste, steel-smelting slag, microsilica, recycling, hybrid additives, green technology, energy saving.

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Introduction

In Uzbekistan, numerous enterprises operating in the energy, metallurgical, chemical, mining, and processing sectors generate vast quantities of mineral-based industrial waste, much of which is currently disposed of in landfills or open dumps, causing serious ecological and economic concerns. However, with the adoption of scientifically grounded and rational processing technologies, these technogenic wastes possess significant potential to serve as alternative raw materials for various industrial applications, particularly in construction material production [[1], [2], [3]].

Recognizing the dual necessity of environmental conservation and resource efficiency, both global and national initiatives are being actively pursued. In Uzbekistan, a strategic emphasis has been placed on enhancing environmental protection, promoting sustainable development, rationalizing the use of natural resources, and improving the sanitary-ecological landscape of industrial regions [4].

Simultaneously, due to the persistent escalation in the costs of fuel, energy, and raw material resources, the global construction industry is experiencing a paradigm shift towards the use of composite Portland cements (CPCs). These cements incorporate hybrid mineral additives—combinations of two or more supplementary cementitious materials (SCMs) of either natural or anthropogenic origin—which enable a significant reduction in Portland cement clinker content. This approach not only conserves primary resources and decreases production costs but also contributes to substantial reductions in CO_2 emissions associated with clinker calcination, thus mitigating the carbon footprint of cement production [[5], [6], [7]].

Consequently, the integration of industrial waste into CPC formulations represents a promising direction for achieving eco-efficient construction materials, aligned with the principles of "green" technology and sustainable development. This transformation necessitates comprehensive research into the physical, chemical, and pozzolanic properties of potential waste-derived additives to optimize their performance in cementitious systems.

The production of composite Portland cements (CPC), incorporating various mineral additives, represents a scientifically grounded and environmentally conscious solution to the long-standing challenge of reducing clinker content in cement. By replacing a portion of energy- and carbon-intensive clinker with alternative pozzolanic or hydraulic materials, CPCs enable a simultaneous decrease in the consumption of natural resources and thermal energy, while also mitigating the substantial carbon dioxide emissions traditionally associated with Portland cement manufacturing processes [[8], [9], [10]].

This approach is particularly relevant in regions where access to high-quality raw materials is limited or where cement demand is rapidly increasing due to large-scale infrastructure development. In such contexts, the utilization of locally sourced natural or industrial mineral additives—such as ash, slag, volcanic tuff, or other silicate-based materials—serves as a strategic method to alleviate supply deficits and reduce logistical costs related to raw material transportation. The incorporation of up to three distinct additives with varying mineralogical compositions into a single cement formulation is permitted by existing standards, opening avenues for the development of hybrid binders with tailored performance properties [[11], [12]].

However, the widespread industrial adoption of multi-component CPCs remains constrained by several factors. Chief among them is the lack of comprehensive technological frameworks and insufficient experimental data regarding the synergistic or antagonistic effects of multiple additives introduced simultaneously. Additionally, geographical disparities in the availability of suitable waste materials—such as fly ash, blast furnace slag, and clay—further hinder consistent production. Cost barriers, particularly associated with high-performance additives like microsilica, also limit large-scale implementation.

Forecasts by the International Energy Agency anticipate a steady increase in the global share of CPCs, with permissible additive content projected to rise to 40% or more by 2100. This shift is expected to significantly elevate the demand for supplementary cementitious materials. Nevertheless, current reserves of widely used additives are insufficient to satisfy this anticipated growth, prompting the urgent need for targeted research aimed at identifying, characterizing, and processing new sources of mineral additives.

Such research must focus not only on the geochemical and physical properties of potential raw materials but also on their environmental compatibility, long-term durability, and economic feasibility. In this context, the valorization of underutilized or untapped local resources—such as technogenic by-products, silicate rocks, and industrial residues—will be crucial for establishing a sustainable, low-carbon cement industry capable of meeting future global construction demands.

In this context, the comprehensive investigation of the technological properties, chemical compositions, and potential applications of mineral technogenic raw materials derived from various industrial processing sectors becomes critically important. As industrial production continues to expand globally, the generation and accumulation of technogenic by-products—such as slags, ashes, industrial dusts, and other waste materials—grow proportionally. These secondary raw materials represent an increasingly valuable resource pool that can significantly supplement traditional natural mineral sources, which are often limited in availability or subject to depletion [13]. Understanding their physical, chemical, and mineralogical characteristics is essential to optimize their incorporation into cementitious systems, ensuring that these additives not only enhance material performance but also comply with environmental and health safety standards [[14], [15]].

Furthermore, the strategic utilization of synthetic mineral raw materials addresses multiple pressing challenges faced by the cement industry and broader environmental management goals. The deployment of these materials promotes a “clean” climate by reducing the carbon footprint associated with clinker production and by enabling the recycling of industrial waste that would otherwise contribute to environmental pollution [16]. This approach also safeguards the health and safety of populations living in proximity to heavy industrial zones by mitigating the uncontrolled release of hazardous substances and dust emissions [17]. Additionally, it plays a vital role in preserving biodiversity, as the extraction pressure on natural mineral deposits is alleviated, reducing habitat destruction and ecological imbalance [18].

From an applied research perspective, evaluating the feasibility and effectiveness of energy and metallurgical waste as supplementary cementitious materials requires systematic experimental work and techno-economic analysis [19]. Such studies encompass the optimization of processing techniques to improve reactivity, assess durability under various environmental conditions, and evaluate long-term stability in concrete composites [20]. Alongside this, it is necessary to develop specific guidelines and recommendations for industrial-scale implementation that consider local resource availability, regulatory frameworks, and sustainability metrics.

Ultimately, these efforts culminate in the formulation of novel “green” composite cement products that align with global climate targets and sustainable development goals. Numerous studies confirm that the integration of diverse mineral additives and synthetic raw materials fosters the development of durable, eco-friendly building materials capable of meeting modern infrastructure demands while minimizing ecological impact [[21], [22], [23], [24], [25], [26]].

Experimental part

The study objects comprised Portland cement clinker sourced from Bekabadcement JSC, gypsum stone from the Bukhara deposit, and the proposed additives including active ash slag (AAS) from the Angren TPP dry removal, microsilica (MS), processed steel slag (PS), ladle slag (LS), and furnace slag (FS) produced by Uzmetkombinat JSC. The chemical and mineralogical compositions of the raw materials were determined according to GOST 5382, with hydraulic activity assessed in accordance with GOST 310.4. This involved processing to derive the calculated value of the Student's criterion as per GOST 25094. To evaluate the suitability of raw materials as cement additives, their compressive strength must be assessed in comparison to the strength of standard sand mixed with cement; this necessitates subsequent statistical processing of the obtained data and calculation of the Student's criterion in alignment with the GOST 25094 methodology. The results were evaluated following O'z DSt 901 and GOST 31108 - 20. The suitability of ash and slag was determined according to national standard O'z DSt 2912:2014 “Ash and slag mixtures for the production of Portland cement clinker and Portland cement. Technical conditions". The pozzolanic activity of the additives was quantified by measuring the volume of lime absorbed, along with the degree of alkalinity of the liquid phase in contact with the cement samples containing hybrid additives.

Physical and mechanical testing of samples.

Grinding the mixtures in a laboratory ball mill to fineness according to the residue on sieve No. 008. A mixture of test clinker with different ratios additives and clinker with standard sand was prepared using a mixer machine Matest E093 for 1 minute. The mixture was trowel-mixed for another 4 minutes to ensure uniformity in the cement mortar. The resulting slurry was then transferred into a three-pong mold, measuring 40×40×160 mm for compressive strength tests and 20×20×20 mm for definition of hydraulic activity. The molds were clamped onto a vibrating machine, Matest for 2 minutes to compact the mortar.

To safeguard against moisture loss caused by evaporation, a polythene sheet that was impermeable and flat was used to cover the prisms. These prisms were then placed in a temperature-controlled room with relative humidity exceeding 90% for 24 hours±30 minutes, after which they were demolded and air-cured for 28 days. Potable water was used as the mixing liquid, and they were cured in water for 28 days.

Following grinding of the mixtures in a laboratory ball mill to achieve a residue fineness on sieve No. 008, six prism samples were created from each mortar mixture and subjected to compressive strength testing subsequent to maturation and steaming, as outlined in GOST 310.4-81 "Cements. Methods for Determining Bending and Compressive Strength." The efficacy of the additive under investigation was ascertained by statistically evaluating the significance of strength disparities between samples containing MS and those containing sand.

Based on the compressive strength data, the Student's criterion (t-criterion) was calculated, and the computed t-criterion value was juxtaposed with the standard threshold of t = 2.07 in accordance with O'z DSt 901-98 and t = 15 per GOST 31108-20. A t value surpassing these benchmarks indicates that the additive has successfully met the strength activity assessment. The calculation for the mixtures consisted of:

1 - Xiad – clinker + MS additive
2 - His – clinker + sand

Results and Discussion

The results of the chemical analyses conducted on Portland cement clinker, gypsum stone, and the industrial waste materials under study are presented in Table 1. Utilizing the chemical composition data, the mineralogical makeup and modular parameters of the clinker—including the saturation factor (K), and the lime (n) and silica (p) ratios—were calculated. These calculated indices confirm that the Portland cement clinker conforms fully to the specifications outlined in the National Standard O’z DSt 2801:2013, which governs clinker quality requirements for the production of general-purpose construction cements.

The combined content of gypsum and anhydrite identifies the gypsum stone extracted from the Bukhara deposit as a Grade 3 gypsum, indicating its suitability as a setting time regulator in Portland cement formulations. According to its chemical characteristics, the ash and slag mixture (AAS) is classified as acidic ash and slag with a low content of combustible substances, as evidenced by the measured loss on ignition values. Moreover, its chemical composition meets the criteria specified in the O’z DSt 2912:2014 standard for ash and slag mixtures used in the manufacturing of Portland cement clinker and Portland cement.

To thoroughly assess the potential of these raw materials as cement additives, their compressive strength must be evaluated relative to the strength of a control mixture containing standard sand and cement. This necessitates further statistical analysis of the experimental data, including the calculation of Student’s t-test to determine the significance of the observed differences. To illustrate this evaluation approach, specific experiments were performed to determine the Student’s t-value for microsilica. Two types of mixtures were prepared for testing:

A blend of 600 grams of Portland cement clinker, 1400 grams of microsilica additive, and 100 grams of gypsum stone expressed chemically as $CaSO_4 \cdot 2H_2O$;

A control blend of 600 grams of Portland cement clinker, 1400 grams of standard sand, and 100 grams of gypsum stone ($CaSO_4 \cdot 2H_2O$).

This comparative analysis enables a clear determination of the effect of the microsilica additive on the mechanical properties of the cement composite.

Table 1 - Chemical compositions of Portland cement clinker and gypsum stone

Name of materials	Content of mass fraction of oxides, %							
	loss on ignition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	others
Clinker JSC "Bekabadcement"	0.36	21.30	4.75	4.86	63.68	3.07	0.43	2.55
Gypsum stone	400°C 13.60	2.11	0.49	0.15	31.08	3.79	38.09	10.7
Ladle slag	1.49	35.93	7.56	2.79	33.06	6.04	0.78	12.35
Recycled steel slag	3.0	62.02	23.55	4.32	3.0	-	1.28	0.80
Furnace slag	-	31.34	9.57	20.78	15.97	4.23	1.19	16.92
Microsilica	2.79	90.84	1.51	1.59	0.56	1.00	0.23	1.48
Active ash and slag	3.0	62.02	23.55	4.32	3.0	-	1.28	0.8

Table 2 - Arithmetic mean values of compressive strength and their standard deviations

№ samples	X_{iad}	$X_{iad} - X_{iad}$	$(X_{iad} - X_{iad})^2$	X_{is}	$X_{is} - X_s$	$(X_{is} - X_s)^2$
1	9.2	0.3	0.09	6.4	0.13	0.0169
2	9.2	0.3	0.09	6.4	0.13	0.0169
3	10.0	-0.5	0.25	6.2	0.33	0.1089
4	9.0	0.5	0.25	7.6	-1.07	1.1449
5	9.6	-0.1	0.01	6.2	0.33	0.1089
6	9.2	0.3	0.09	6.4	0.13	0.0169
7	9.0	0.5	0.25	6.2	0.33	0.1089
8	10.2	-0.7	0.49	7.6	-1.07	1.1449
9	10.4	-0.9	0.81	6.2	0.33	0.1089
10	9.0	50.1	0.25	6.4	0.13	0.0169
11	9.2	0.3	0.09	6.4	0.13	0.0169
12	10.4	-0.9	0.81	6.4	0.13	0.0169
$\sum_{i=1}^{12}$	114		3.48	78.4		2.83
X average	9.50			6.53		

The experimental results of prism specimens, systematically prepared from two comparative mixtures designated as Composition No. 1 and Composition No. 2, are rigorously compiled and detailed in Table 2. These data form the basis for subsequent quantitative analysis and statistical evaluation.

The table provides detailed measurements for each sample, including individual compressive strength values (Xi), deviations from the mean, squared deviations, and calculated statistical parameters for both mixtures.

Based on the data presented in Table 2, the arithmetic mean compressive strength values and their standard deviations were calculated as follows:

Student's t-Test Calculation

• For mixture No. 1 (X̄i_ad):

$$\bar{X}_{ad} = \frac{114}{12} = 9.50 \text{ MPa}; \quad S_{ad}^2 = \frac{3.48}{11} = 0.316;$$
$$S_{ad} = \sqrt{0.316} = 0.562$$

• For mixture No. 2 (X̄i_s):

$$\bar{X}_s = \frac{78.4}{12} = 6.53 \text{ MPa}; \quad S_s^2 = \frac{2.83}{11} = 0.257; \quad S_s = \sqrt{0.257} = 0.507$$

Where $\bar{X}_{ad}$ and $\bar{X}_s$ denote the mean ultimate compressive strength values of samples from compositions 1 and 2, respectively.

Before proceeding with hypothesis testing, the following conditions were verified to ensure the validity of the Student's t-test:

1. The similarity of standard deviations:

$$S_{ad} \approx S_s \leq 2.0 \text{ MPa} \Rightarrow 0.562 \approx 0.507 < 2.0 \text{ MPa}$$

2. The ratio of variances meets the required threshold:

$$\frac{S_{ad}^2}{S_s^2} = \frac{0.316}{0.257} = 1.23 < 2.82$$

Since both conditions were satisfied, the Student's t-test was computed using the formula:

$$t = 2.45 \times = \frac{X_{ad} - X_s}{\sqrt{\frac{S_{ad}^2 + S_s^2}{2}}} = 2.45 \times = \frac{9.50 - 6.53}{\sqrt{\frac{0.316 + 0.257}{2}}} =$$
$$2.45 \times \frac{2.97}{0.54} = 13.47$$

The calculated t-value of 13.47 significantly exceeds the critical value of 2.07 stipulated by the O'z DSt 901 standard. This clearly indicates that microsilica (MS) functions as an active mineral additive, validating its recommendation for use as such in cement formulations.

Applying this same statistical methodology, the activity and suitability of other technogenic waste materials were evaluated. The resulting Student's t-test values were:

- Active ash and slag (AASh): 52.92
- Recycled steel slag (RSS): 11.14 for the fraction 0–5 mm, and 2.19 for the fraction 5–50 mm
- Ladle slag (LS): 5.00
- Furnace slag (PS): 4.48

Based on the descending order of the Student's t-values, the additives can be ranked in terms of their mineral activity and potential effectiveness as follows:

Active ash and slag → Microsilica → Recycled steel slag → Ladle slag → Furnace slag

This ranking provides a clear hierarchy of mineral additive activity, supporting targeted selection for optimized cementitious composite production.

Previous investigations conducted at the "Strom" Scientific Laboratory and Testing Center of the Institute of General and Inorganic Chemistry under the Academy of Sciences of the Republic of Uzbekistan have demonstrated that the incorporation of processed steel slag (RSS) and microsilica (MS) in quantities exceeding 15% tends to reduce the compressive strength of Portland cement. Conversely, activated ash and slag (AASh), due to its pronounced pozzolanic reactivity, has shown potential to substitute up to 45% of clinker in cement formulations without compromising mechanical performance.

Based on these findings, a new approach was adopted to design hybrid mineral additives in which AASh serves as the principal active component, while other less reactive materials, such as MS, RSS, furnace slag (FS), and ladle slag (LS), function as supplementary components. In the developed compositions, the proportion of AASh was systematically varied from 15% to 35%, while the content of the passive components remained fixed at 10% (Table 3).

The pozzolanic activity of these newly developed hybrid additives was evaluated using the liquid phase saturation method. In this procedure, composite Portland cement samples containing different types and quantities of hybrid additives were immersed in a controlled liquid medium, and the degree of CaO (lime) absorption was measured over a period of 30 days [23]. This method is grounded in the principle that reactive mineral additives can bind with free lime (CaO) released during the hydration of clinker phases, thereby reducing the lime concentration in the surrounding liquid and indicating higher pozzolanic activity.

According to the data in Table 5, samples of standard Portland cement without any additives (PC-Ad0) released approximately 5.4% CaO into the liquid phase within 30 days, and the total alkalinity of the solution reached 58.8 meq/L. In comparison, the liquid containing composite cement samples with a hybrid additive comprising 15% AASh and 10% RSS exhibited a reduced CaO concentration of 4.2%, implying that approximately 1.2% of the released CaO was absorbed by the additives. The corresponding total alkalinity also declined to 56.0 meq/L, 2.8 meq/L lower than that of the control.

Table 3 - Hydraulic activity of additives determined by the degree of lime saturation of the liquid phase in contact with cement

№	Component ratio, mass. %				CaO content in liquid, %	Total alkalinity of solution, meq L^{-1}
	Clinker	active ash and slag	recycled steel slag	gypsum stone		
1	95	-	-	-	5.4	58.8
2	70	15	10	5	4.2	56
3	60	25	10	5	2.22	48
4	50	35	10	5	0.72	32.4
	Clinker	active ash and slag	furnace slag	gypsum stone		
5	70	15	10	5	4.68	56.4
6	60	25	10	5	2.64	48.8
7	50	35	10	5	1.38	40
	Clinker	active ash and slag	ladle slag	gypsum stone		
8	70	15	10	5	3.9	61.6
9	60	25	10	5	2.58	55.2
10	50	35	10	5	0.84	41.2
	Clinker	active ash and slag	microsilica	gypsum stone		
11	70	15	10	5	0.78	20
12	60	25	10	5	0.72	35.2
13	50	35	10	5	0.36	23.2

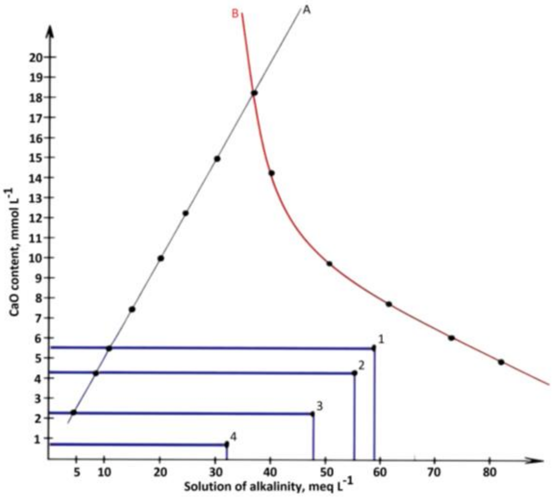

Figure 1 - Pozzolanic activity of additives “active ash and slag + recycled steel slag” in the composite Portland cement: A- lime solubility isotherm at 40°; B- alkalinity, which accounts for all components except lime.

Content of CaO in cement mortar with an additive:

1-PC-Ad0, 2-HAd25 %, 3- HAd 35 %, 4- HAd 45 %.

Further increasing the proportion of AASh to 25% and 35% significantly enhanced the lime-binding capacity of the hybrid additives. In these cases, the CaO concentrations in the liquid phase dropped to 2.22% and 0.72%, respectively, equating to CaO absorptions of 2.98% and 4.68%. Simultaneously, the total alkalinity of the liquid phase decreased to 48.0 meq/L and 32.4 meq/L, respectively. These trends clearly underscore the high pozzolanic reactivity of the AASh + RSS hybrid system, wherein increasing the proportion of AASh at a constant 10% RSS content directly enhances lime fixation and reduces alkalinity in the liquid phase (Figure 1).

Hybrid additives of the composition “active ash and slag + furnace slag” and “active ash and slag + ladle slag” are characterized by almost the same absorbing ability, the activity of which also increases with increasing content of active ash and slag from 15 % to 35 % - the CaO content in the liquid phase with these hybrid additives is (4.68 - 1.38) % and (3.9 -0.84) %, and the total alkalinity of the liquid phase is (1.38 - 40.0) meq L^{-1} and (61.6 - 41.2) meq L^{-1}, respectively (Figure 2).

Legend:

1 – PC-Ad0 (reference Portland cement without additives);

2 – PC-HAd25 (composite cement with 25% hybrid additive);

3 – PC-HAd35 (composite cement with 35% hybrid additive);

4 – PC-HAd45 (composite cement with 45% hybrid additive).

(a) – Isothermal solubility curves of calcium hydroxide at 40 °C;

(b) – Alkalinity of the liquid phase contributed by all components excluding free lime (CaO).

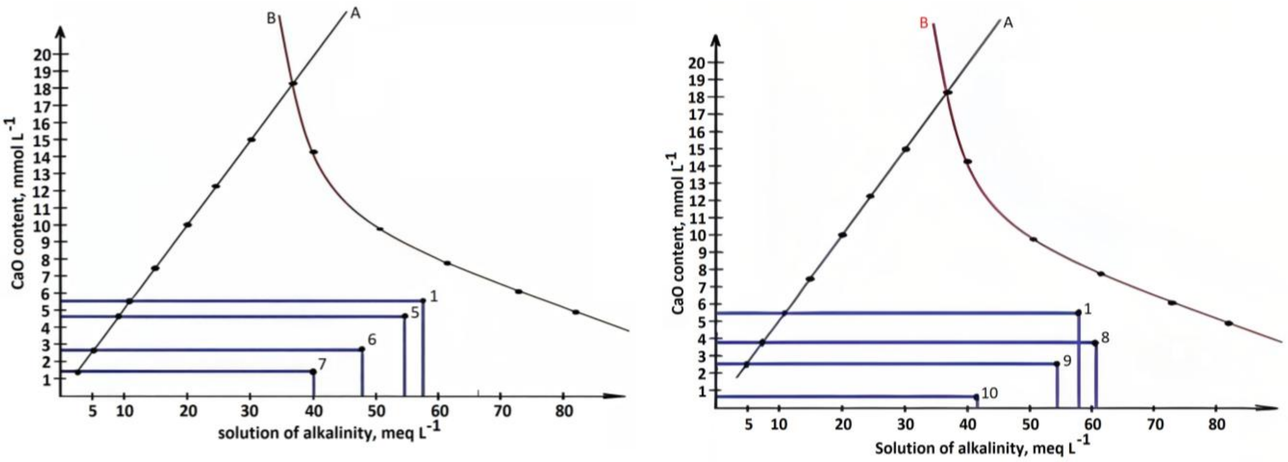

Figure 2 - Pozzolanic activity of hybrid additives comprising “activated ash and slag (AASh) + furnace slag (FS)” (a) and “activated ash and slag (AASh) + ladle slag (LS)” (b) in composite Portland cement systems.

CaO content in cement mortar samples containing hybrid additives:

1 – PC-Ad0;
5 – HAd25%;
6 – HAd35%;
7 – HAd45% (for both subfigures a and b).

The experimental findings indicate that the highest pozzolanic activity among the studied hybrid additives is exhibited by the composition based on activated ash and slag (AASh) combined with microsilica (MS). Already at a dosage of 15 wt% AASh and 10 wt% MS, a substantial decrease in the concentration of calcium oxide (CaO) in the liquid phase was observed — 0.78%, which is 4.62% less than the CaO concentration in the solution where control samples of additive-free Portland cement (PC-Ad0) were stored. This reduction confirms the effective lime-binding capacity of the hybrid additive system.

Moreover, the total alkalinity of the solution decreased sharply to 20 meq/L, which is more than 3.5 times lower than the alkalinity value observed for the solution containing PC400-Ad0 samples. This pronounced drop in alkalinity suggests not only efficient lime immobilization but also an intensification of pozzolanic reactions in the cementitious environment.

As the dosage of AASh was increased to 25 wt% and 35 wt% (with MS content held constant at 10 wt%), the CaO concentration in the liquid phase further declined to 0.72% and 0.36%, respectively. These results underscore the synergetic effect of ultrafine MS in enhancing the pozzolanic efficiency and reactivity of the hybrid system. The high specific surface area and amorphous structure of MS contribute to the increased rate of calcium hydroxide fixation, thereby promoting the formation of additional calcium silicate hydrate (C–S–H) phases.

Despite the reduction in free CaO, a slight increase in total alkalinity was recorded for systems containing higher AASh content. This phenomenon can be attributed to the accelerated hydration kinetics of clinker minerals—primarily tricalcium silicate (C_3S) and dicalcium silicate (C_2S)—facilitated by the reactive environment generated by MS. The intensified dissolution of these phases leads to a higher release of Ca^{2+} ions into the pore solution, thereby increasing its ionic strength and pH.

The cumulative findings affirm that all investigated hybrid additive formulations demonstrate considerable pozzolanic potential and meet the performance benchmarks for mineral additives in blended cement systems. According to the technical classification system outlined in GOST 24640-91 "Additives for cements. Classification", the developed hybrid additives fall under the category of active mineral admixtures, simultaneously exhibiting both hydraulic and pozzolanic properties. Their multifunctional nature makes them promising candidates for sustainable cement formulations aimed at reducing clinker content and enhancing durability characteristics of the final composite.

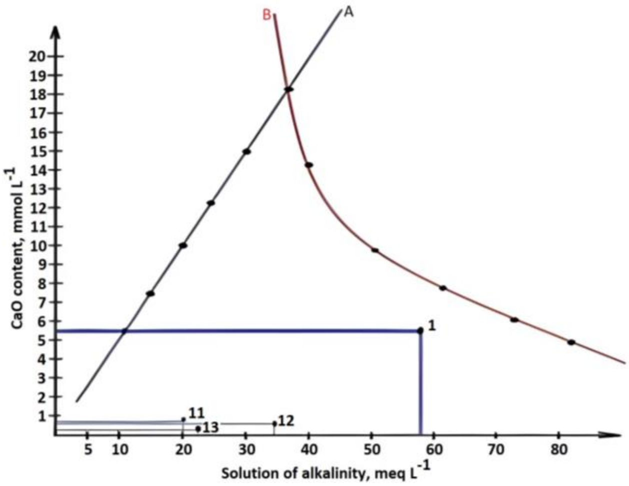

Figure 3 - Pozzolanic activity of hybrid additives based on "active ash and slag + microsilica (MS)" in composite Portland cement

A – Isotherm of lime (CaO) solubility at 40 °C;
B – Total alkalinity of the liquid phase, excluding the contribution of lime.

Legend (for both graphs):
1 – PC-Ad0 (reference cement without additives);
5 – Cement with 25% active ash and slag + 10% MS (HAd25);
6 – Cement with 35% active ash and slag + 10% MS (HAd35);
7 – Cement with 45% active ash and slag + 10% MS (HAd45).

Conclusions

The research has convincingly demonstrated that the modification of technogenic steelmaking by-products, particularly ladle slag and furnace slag, with ash and slag waste generated by thermal power plants, enables the development of hybrid mineral additives possessing enhanced hydraulic and pozzolanic activity. These hybrid additives make it possible to produce composite Portland cements whose mechanical strength is comparable to, or even exceeds, that of reference Portland cement grade PC400-Ad0, despite containing a significantly reduced proportion of clinker.

The active ash and slag (AASh) component—characterized by high reactivity—plays a pivotal role in the early stages of hydration. By intensively binding calcium hydroxide [$Ca(OH)_2$] from the pore solution, it accelerates the formation of calcium hydrosulfoaluminates, thereby contributing to the early strength gain of the cementitious matrix. Meanwhile, the more inert components of the hybrid additives, such as microsilica (MS), processed ladle slag (LS), and furnace slag (FS), continue to react over time, promoting the formation of secondary calcium silicate hydrates (C–S–H). These hydrates fill capillary pores, enhance microstructural densification, and contribute to the long-term strength and durability of the cement composite.

Comprehensive control testing of large-scale batches containing the optimal hybrid additive compositions was conducted at JSC Akhangarancement and JSC Bekabadcement. The results of these industrial-scale trials unequivocally confirmed the feasibility and effectiveness of replacing 25% to 45% of Portland cement clinker with the developed "green" hybrid additives. The resulting composite Portland cements reliably achieved strength classes of 400 to 500, in full compliance with regulatory standards and performance requirements.

These findings affirm the technological and environmental viability of the proposed hybrid systems and their potential for widespread application in sustainable cement manufacturing.

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

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Портландцементке қоспа ретінде өнеркәсіптік шикізаттың жарамдылығын зерттеу

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ТҮЙІНДЕМЕ
Бұл зерттеу композициялық портландцемент (КПЦ) өндірісінде өнеркәсіптік техногенді қалдықтарды гибридті минералдық қоспалар ретінде пайдалану мүмкіндігін зерттейді. Зерттеудің басты мақсаты – клинкер тұтынуын азайту және экологиялық таза құрылыс технологияларын ілгерілету. Қарастырылған материалдарға Ангрен жылу электр станциясынан алынған белсенді күл мен қож (БКҚ), микрокремнезем (МК), сондай-ақ «Өзметкомбинат» АҚ-ның болат өндірісі қалдықтары – ковш қожы (КҚ), пеш қожы (ПҚ) және қайта өңделген болат қожы (ҚБҚ) жатады. Аталған материалдардың химиялық, минералогиялық және механикалық қасиеттері ұлттық және халықаралық стандарттарға

сәйкес сипатталды. Олардың пуццоландық және гидравликалық белсенділігі қысымға төзімділік сынақтары және әктің сіңірілуін өлшеу арқылы бағаланды. Эксперименттік нәтижелер БКҚ-ның белсенділігі ең жоғары екенін көрсетті: ол клинкердің 45%-ға дейінгі мөлшерін механикалық беріктікке кері әсер етпей алмастыра алады. Белсенділігі төмен материалдармен (МК, ҚБҚ, ПҚ және КҚ) бірге қолданылғанда гибридті қоспалар синергетикалық әсер көрсетті. Атап айтқанда, БКҚ мен МК қоспасы ең жоғары пуццоландық белсенділік танытты: ол қоршаған сұйықтықтағы кальций оксиді (CaO) концентрациясының төмендеуімен және ерітінді сілтілігінің азаюымен расталды. Стьюденттің t-өлшемшарты арқылы жүргізілген статистикалық тексеру әрбір қоспаның тиімділігін дәлелдеді: алынған t-мағыналар олардың белсенді минералдық қоспалар ретінде жіктелуіне қажетті шектік мәндерден едәуір асып түсті. Зерттеу нәтижелері жергілікті өнеркәсіптік қалдықтар негізінде гибридті қоспалар арқылы «жасыл» КПЦ жасаудың мүмкіндігін қолдайды. Мұндай құрамдар көмірқышқыл газы шығарындыларын, энергия тұтынуды және табиғи ресурстардың сарқылуын айтарлықтай азайта отырып, цементтің пайдалану қабілетін сақтап қалады. Бұл тәсіл төмен клинкерлі және төмен көміртекті құрылыс материалдарына көшу жөніндегі жаһандық үрдістерге толық сәйкес келеді.

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Изучение пригодности промышленных сырьевых ресурсов в качестве добавок к портландцементу

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АННОТАЦИЯ

В данном исследовании рассматривается возможность использования техногенных промышленных отходов в качестве гибридных минеральных добавок при производстве композиционного портландцемента (КПЦ) с целью снижения расхода клинкера и продвижения экологически безопасных строительных технологий. Изученные материалы включают активную золу и шлак (АЗШ) с Ангренской теплоэлектростанции, микросилику (микрокремнезем) (МС), а также переработанные отходы металлургического производства, такие как ковшевой шлак (КШ), печной шлак (ПШ) и переработанный сталеплавильный шлак (ПСШ) от АО "Узметкомбинат". Химические, минералогические и механические свойства этих материалов были охарактеризованы в соответствии с национальными и международными стандартами. Пуццолановая и гидравлическая активность оценивались методом испытания на прочность при сжатии и измерением поглощения извести. Экспериментальные результаты показали, что АЗШ обладает наивысшей активностью и способен заменять до 45% клинкера без ухудшения прочностных характеристик. В сочетании с менее активными компонентами (МС, ПСС, ПШ и КШ) гибридные добавки проявляют синергетический эффект. Среди них смесь АЗШ+МС показала наибольший пуццолановый эффект, что выражается в снижении концентрации оксида кальция (CaO) в окружающей жидкости и пониженной щелочности раствора. Статистическая проверка с использованием t-критерия Стьюдента подтвердила эффективность каждой добавки, поскольку значения t значительно превышали порог,

	необходимый для классификации их как активных минеральных добавок. Полученные результаты подтверждают возможность разработки «зеленого» КПЦ с использованием гибридных добавок на основе местных промышленных отходов, предлагая устойчивую альтернативу традиционным сырьевым материалам. Такие составы могут существенно снизить выбросы углекислого газа, потребление энергии и истощение природных ресурсов при сохранении эксплуатационных свойств цемента, что соответствует глобальным тенденциям к низкоклинкерным и низкоуглеродным строительным материалам.
	Ключевые слова: промышленные отходы, сталеплавильный шлак, микросилика, переработка, гибридные добавки, зелёные технологии, энергосбережение.
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