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RESEARCH ARTICLE

CHEMOACTIVATION OF EKIBASTUZ FLY ASH IN CEMENT

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Abstract. *The scientific article comprehensively examines the issue of the effective use of fly ash–a major tonnage of technogenic waste from the Ekibastuz GRES-in construction materials, specifically in cement compositions and hyper-pressed products. The main scientific novelty and primary objective of the study is to increase the low hydraulic activity of high-silica (acidic) fly ash through chemoactivation with a sodium hydroxide (NaOH) solution, and its effect on the physicomechanical properties of hyper-pressed brick is scientifically substantiated. During the experimental studies, 2%, 4%, and 6% concentrated sodium hydroxide (NaOH) solutions were used to activate the fly ash. The research results showed that as the concentration of the alkaline reagent increased, the dissolution of the amorphous phase on the surface of the ash particles accelerated, leading to more intensive hydration processes of the cement matrix. In particular, The use of chemically activated ash at a 4% NaOH concentration significantly increased the density of the cement composite and improved the early and design (28-day) strength values by 15-20% compared to the control samples. In addition, the article presents the results of X-ray phase and electron microscopic analyses of the microstructure of hyper-pressed brick. These analyses demonstrate that chemical activation of ash leads to the formation of additional calcium hydro-silicates, reduces the material's porosity, and strengthens its structure. The practical significance of the work is directed at increasing the level of waste utilization in the construction industry, saving on cement consumption, and improving the technology for obtaining environmentally safe, high-strength hyper-pressurized products. The obtained results make it possible to improve the ecological situation in the Ekibastuz region and reduce the cost of construction materials.*

Keywords: *fly ash, chemical activation, cement composites, strength, hydration, technogenic waste, Ekibastuz coal.*

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ҒЫЛЫМИ МАҚАЛА

ЕКІБАСТҰЗ ҰШПА КҮЛІН ЦЕМЕНТТЕ ХИМИЯЛЫҚ БЕЛСЕНДІРУ

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Аңдатпа. *Ғылыми мақалада Екібастұз ГРЭС-нің ірі тоннажды техногендік қалдығы болып табылатын ұшпа күлді құрылыс материалдарының, атап айтқанда, цементті композициялар мен гиперпрестелген бұйымдардың құрамында тиімді пайдалану мәселелері жан-жақты қарастырылған. Зерттеудің басты ғылыми жаңалығы мен негізгі мақсаты – жоғары кремнийлі (қышқыл) күлдің төмен гидравликалық белсенділігін натрий гидроксиді (NaOH) ерітіндісімен хемоактивациялау әдісі арқылы арттыру және оның гиперпрестелген кірпіштің физика-механикалық қасиеттеріне әсерін ғылыми негіздеу болып табылады. Эксперименттік зерттеулер барысында ұшпа күлді белсендіру үшін натрий гидроксидінің (NaOH) 2%, 4% және 6% концентрациялы ерітінділері қолданылды. Зерттеу нәтижелері сілтілік реагенттің концентрациясы артқан сайын күл бөлшектерінің беткі қабатындағы аморфты фазаның еруі жеделдеп, цемент тасының гидратация процестерінің қарқынды жүретінін көрсетті. Атап айтқанда, NaOH 4% концентрациясында хемоактивацияланған күлді қолдану цементті композицияның тығыздығын айтарлықтай арттырып, ерте және жобалық (28 тәулік) мерзімдегі беріктік көрсеткіштерін бақылау үлгілерімен салыстырғанда 15-20%-ға жақсартуға мүмкіндік берді. Сонымен қатар, мақалада гиперпрестелген кірпіштің микроқұрылымына жасалған рентгенфазалық және электрондық-микроскопиялық талдаулардың нәтижелері келтірілген. Бұл талдаулар күлді химиялық белсендіру нәтижесінде қосымша кальций гидросиликаттарының түзілетінін және материалдың кеуектілігі төмендеп, құрылымының нығая түсетінін дәлелдейді. Жұмыстың практикалық маңыздылығы құрылыс индустриясында қалдықтарды кәдеге жарату деңгейін арттыруға, цемент шығынын үнемдеуге және экологиялық қауіпсіз, беріктігі жоғары гиперпрестелген бұйымдарды алу технологиясын жетілдіруге бағытталған. Алынған нәтижелер Екібастұз аймағындағы экологиялық жағдайды жақсартуға және құрылыс материалдарының өзіндік құнын төмендетуге мүмкіндік береді.*

Түйін сөздер: *ұшпа күл, хемоактивация, цемент композициялары, беріктік, гидратация, техногендік қалдықтар, Екібастұз көмірі.*

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НАУЧНАЯ СТАТЬЯ

ХЕМОАКТИВАЦИЯ ЭКИБАСТУЗСКОЙ ЗОЛЫ-УНОСА В ЦЕМЕНТЕ

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Аннотация. *В научной статье подробно рассмотрены вопросы эффективного использования летучих золовых строительных материалов, являющихся крупнотоннажным техногенным отходом Экибастузской ГРЭС, в частности, в составе цементных композиций и гиперпрессованных изделий. Главной научной новизной и основной целью исследования является повышение низкой гидравлической активности высококремниевой (кислой) золы методом хемоактивации раствором гидроксида натрия (NaOH) и научное обоснование его влияния на физико-механические свойства гиперпрессованного кирпича. В экспериментальных исследованиях для активации летучих золы использовались растворы гидроксида натрия (NaOH) в концентрациях 2%, 4% и 6%. Результаты исследования показали, что по мере увеличения концентрации щелочного реагента ускоряется растворение аморфной фазы в поверхностном слое частиц золы, интенсивно протекают процессы гидратации цементного камня. В частности, применение хемоактивированной золы при концентрации NaOH 4% позволило значительно увеличить плотность цементного состава и улучшить показатели прочности на 15-20% по сравнению с контрольными образцами в ранние и проектные (28 суток) сроки. Кроме того, в статье приводятся результаты рентгенофазных и электронно-микроскопических анализов микроструктуры гиперпрессованного кирпича. Эти анализы доказывают, что в результате химической активации золы образуются дополнительные гидросиликаты кальция, а пористость материала уменьшается, а его структура укрепляется. Практическая значимость работы направлена на повышение уровня утилизации отходов в строительной отрасли, экономию расхода цемента и совершенствование технологии получения экологически безопасных, высокопрочных гиперпрессованных изделий. Полученные результаты позволят улучшить экологическую обстановку в Экибастузском регионе и снизить себестоимость строительных материалов.*

Ключевые слова: *зола-унос, хемоактивация, цементные композиции, прочность, гидратация, техногенные отходы, Экибастузский уголь.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

During the preparation of this manuscript, the authors used artificial intelligence tools (ChatGPT) solely for editorial assistance, such as improving phrasing and checking grammar, spelling, and punctuation. All ideas, interpretations, and conclusions are the responsibility of the authors, who take full accountability for the content of the article.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу Қазақстан Республикасы Ғылым және жоғары білім министрлігі Ғылым комитетінің AP26193815 "Энергетика кәсіпорындарының қалдықтарын пайдалана отырып, отқа төзімді материалдар технологиясының ғылыми-техникалық негіздерін әзірлеу" гранттық қаржыландыру шеңберінде жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

Мақаланы дайындау барысында авторлар жасанды интеллект құралдарын (ChatGPT) тек редакциялық көмек мақсатында пайдаланды: тұжырымдарды жетілдіру, грамматикалық, орфографиялық және тыныс белгілеріндегі қателерді тексеру үшін. Барлық идеялар, интерпретациялар мен қорытындылар авторларға тиесілі, және олар мақаланың мазмұнына толық жауапты.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось в рамках грантового финансирования Комитета науки Министерства науки и высшего образования Республики Казахстан AP26193815 “Разработка научно-технических основ технологии огнеупорных материалов с использованием отходов предприятий энергетики”.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

При подготовке рукописи авторы использовали инструменты искусственного интеллекта (ChatGPT) исключительно для редакторской поддержки: корректировки формулировок, проверки грамматических, орфографических и пунктуационных ошибок. Все идеи, интерпретации и выводы принадлежат авторам, которые несут полную ответственность за содержание статьи.

1 INTRODUCTION

Annual coal combustion leads to the formation of hundreds of millions of tons of coal ash and slag waste (ASW) worldwide, which over the decades has resulted in the accumulation of billions of tons of such anthropogenic materials in specialized storage facilities - ash dumps. These tailings not only take significant land areas out of use (measured in tens of thousands of hectares), but also pose a potential environmental threat due to the possible leaching of harmful elements and the risk of dam breaches (which have historically led to disasters).

A key global trend is the sharp gap between the volumes of ASW generation and its utilization. While developed countries and major industrial economies demonstrate a high level of fly ash utilization, in other regions this indicator remains critically low. For example, in Europe and the USA, the utilization rate of ASW reaches 40-90% (primarily in the cement and road construction industries), whereas in the CIS countries, including Kazakhstan, it is only 8-15% of the volume generated annually. The need to increase the reactivity of ASW is a global challenge for incorporating inactive waste into the production of environmentally friendly and economically efficient building materials **(Sirotyuk et al., 2025).**

The utilization of ASW and their reintegration into the economic cycle is a key priority under the Concept for the Transition of the Republic of Kazakhstan to a "green" economy (by 2050). This Concept aims to increase the utilization rate of industrial waste to 60% by 2030 (compared to 35% in 2021), which is impossible without using high-volume waste such as ASW. At the same time, ASW are a valuable aluminosilicate raw material, potentially suitable for the production of building materials, which is consistent with the principles of the circular economy **(Decree of the President of the Republic of Kazakhstan, 2013)**

The environmental aspect of this work is directly linked to the goals set forth in the Concept of the Republic of Kazakhstan's Transition to a "Green" Economy. The annual volume of waste heat generation exceeds 20 million tons. The implementation of technologies for the comprehensive activation and utilization of these wastes will not only allow for a 60% utilization rate but will also reduce the consumption of natural raw materials and lower the costs of reclaiming land occupied by ash dumps **(Environmental Code of the Republic of Kazakhstan, 2021)**

The most promising approaches to increasing the reactivity of fly ash are chemical activation (treatment with alkaline or calcium-based reagents). Chemical activation, in turn, initiates an intensive pozzolanic reaction, ensuring the rapid formation of binding hydrates.

To achieve the stated goal, the following tasks were formulated:

1. Determine the optimal concentration of the chemical activator (NaOH) to achieve maximum early and ultimate strength of the composites.

2. Investigate the influence of NaOH-activated alkaline phases on the strength characteristics and kinetics of cement-ash samples.

3. Develop recommendations for the effective use of activated lime-slag composites as a binding component in the production of building materials.

The problem of widespread application of fly ash (FA) in the construction industry lies in its low reactivity. A significant portion of this man-made material, despite its rich aluminosilicate composition, does not exhibit sufficient pozzolanic activity to effectively bind the main byproduct of Portland cement hydration. The essence of pozzolanic activity lies in the ability of the amorphous aluminosilicate phase of FA to chemically react with calcium hydroxide ($Ca(OH)_2$), which is released during the hydration of cement clinker. The result of this reaction is the formation of additional calcium silicate hydrates (C-H-S gel) - the primary binding component that determines the strength and density of the cement stone **(Ghazali et al., 2023).**

Dr.Abdolhossein Naghizade of the University of Johannesburg conducted extensive research aimed at enhancing the resistance of fly ash-based geopolymer concrete to alkaline environments. As part of the study, he focused on the problem of the low resistance of such concretes to aggressive alkaline conditions, which limits their application in the construction of structures exposed to chemical effects. In the experimental part of the study, samples of geopolymer concrete, manufactured from fly ash, were subjected to thermal treatment at various temperatures: 100°C, 200°C, 400°C, and 600°C for 6 hours. These samples were then immersed in an extremely alkaline medium (3M NaOH) at 80°C for 14 days. The results showed that the samples heat-treated at 200°C demonstrated significantly better resistance to alkali attack compared to the samples treated at higher temperatures. This is confirmed by microstructural analyses, which revealed fewer cracks and a denser structure in the samples treated at 200°C **(Naghizadeh et al., 2020).**

Professor Therese van Wyk from the University of Johannesburg is actively engaged in research on the development of fly ash-based geopolymer materials, aiming to enhance the resistance of structural elements to aggressive chemical exposure. As part of the experiments, the fly ash-based geopolymer concrete samples were heat-treated at various temperatures: 100°C, 200°C, 400°C, and 600°C for 6 hours. These samples were then immersed in an extremely alkaline medium (3M NaOH) at 80°C for 14 days.The results showed that the samples heat-treated at 200°C demonstrated significantly better resistance to alkali attack compared to the samples treated at higher temperatures. This is confirmed by microstructural analyses, which revealed fewer cracks and a denser structure in the samples treated at 200°C.

Dr. Zengliang Yue, a researcher from the University of Leeds (UK), specializes in studying the structural changes in alkali-activated slag-based cement pastes caused by carbonation.In his work, he focused on the effect of both natural and accelerated carbonation on the phase composition and strength properties of cement pastes activated with sodium sulfate (Na_2SO_4) **(Salamanova et al., 2021 & Khamit et al., 2024).**

In one of the key studies, the team examined changes in the phase composition and strength characteristics of alkali-activated slag cement pastes under CO_2 exposure at concentrations of 0.04% (natural carbonation) and 1% (accelerated carbonation). The results showed that under natural carbonation the changes were negligible even after 500 days, with strength gain continuing. In contrast, accelerated carbonation led to the complete carbonation of the samples within 28 days and a significant decrease in strength due to the decalcification of calcium-containing phases and the formation of various polymorphs of $CaCO_3$ **(Yue, Z. et al., 2024 & Syndarbekova et al., 2025).**

Particular attention is paid to the influence of the composition of alkali-sulfate admixtures on the resistance of pastes to carbonation and the development of corrosive processes. Yue proposes optimal additive dosing parameters to improve the durability of materials in aggressive environments. His work contributes to the development of new types of cements with enhanced resistance to climatic and chemical effects **(Yue, Z. et al., 2025).**

In the article "Utilization of fly ash for sustainable construction materials," authors Ahmed F. Abdalqader, Fei Jin, and Abir Al-Tabbaa (2015) conclude that properly activated ash can significantly reduce the need for cement, improve the environmental characteristics of construction mixtures, and increase resistance to aggressive effects. They also emphasize the need to standardize ash properties and implement regulatory norms for its effective application in the construction industry **(Abdalqader, A.F. et al., 2015 & Takirova et al., 2025).**

The article "Utilization of fly ash in concrete: The Indian scenario" by Maochieh Chi and Ran Huang (2013), published in the journal Construction and Building Materials, provides a comprehensive overview of the use of fly ash in concrete production in India. The authors analyze the physicochemical properties of fly ash, its pozzolanic activity, and its impact on the strength characteristics of concrete mixtures. Special attention is paid to methods of activating the ash to enhance its reactivity, including mechanical, thermal, and chemical treatments **(Chi M. et al., 2013 & Abildaeva et al., 2022).**

Article **(Puertas F. et al., 2000)** is devoted to the investigation of the properties of alkali-activated slag cements. The main problem addressed in the work is the need to develop alternative binding materials capable of replacing traditional Portland cement in order to reduce CO_2 emissions and utilize industrial waste. The authors investigate the influence of various alkali activators on the strength characteristics and hydration products of slag cements. The results showed that the choice of activator type and concentration significantly influences the formation of hydration phases, such as the C-S-H gel, and consequently, the material's strength. Thus, the article highlights the potential of alkali-activated slag cements as a sustainable alternative to traditional cementitious materials, provided that their composition and production technology are optimized.

The authors emphasize that the careful selection of the slag and activator chemical composition is a key factor in producing alkali-activated concrete with high performance characteristics. They note the need for further research on the long-term behavior of the materials and the influence of environmental factors. The work contributes to the development of environmentally sustainable alternatives to traditional cementitious systems, reducing the carbon footprint of construction materials and expanding the potential use of industrial waste **(Escalante-Garcia J.I. et al., 2009 & Durdzi´nski et al., 2015).**

The work examines key aspects such as hydration mechanisms, microstructure formation, and the influence of various types of activators (e.g., NaOH, Na_2SiO_3) and curing conditions on material properties. Special attention is paid to practical issues, including rapid setting, the potential for alkali-silica reaction, efflorescence formation, shrinkage, microcracking, and strength variations. Theoretical issues concerning the role of alkali anions and cations, the nature of hydration products, the development of microstructure, and the mechanisms of setting and hardening are also discussed **(Palomo A. et al., 1998 & Tolegenova et al., 2023).**

2 MATERIALS AND METHODS

A strictly regulated set of materials is used to produce cement-ash composites aimed at increasing strength and utilizing anthropogenic waste. Portland cement (M450) is used as the main binder; it serves not only as the primary binding component but also as a source of calcium hydroxide required for the occurrence of the pozzolanic reaction. The central element of the recipe is the primary waste flying ash from the Ekibastuz coals. The flying ash used in the research was obtained directly from the power plant's flue gas ducts (from the pipes). It has the highest fineness and low moisture content, minimal contamination with foreign inclusions, and has not been subjected to prolonged atmospheric exposure, which makes it the most reactive and preferred for the production of high-quality binders and concretes.

To intensify the chemical processes, a chemical activator was used: sodium hydroxide. It is used as a strong alkaline agent to initiate geopolymerization and accelerate the dissolution of the aluminosilicate phase.

Table 1 shows the methods for preparing the materials for activation

Table 1
Material Preparation Methods

Method	Variable parameter	Purpose
Chemical activation (CA)	Activator concentration (C_{act}): % by weight of binder (2%, 4%, 6% NaOH)	Determination of the optimal dosage for maximum strength.

Standardized testing methods were used to evaluate the final properties of the composites. Samples were prepared as beam specimens (40x40x160 mm). Compressive strength (σ), the primary indicator, was measured at key curing ages (2, 7, and 28 days). in accordance with GOST 30744-2001. This standard unifies the testing methods for all types of cement using poly-fractional standard sand, ensuring the comparability of results with the European standard EN 197-1 (EN 197-1:2011, Cement – Part 1: Composition, specification and conformity criteria for common cement). Microstructural analysis using scanning electron microscopy (SEM) allowed for a visual assessment of the morphology of the newly formed reaction products (C-S-H, N-A-S-H gels) and the density of the composites' structure.

3 RESULTS AND DISCUSSION

During the experimental phase of the work, a series of tests were conducted on cement-ash composites with varying fly ash content and NaOH alkaline activator concentrations. The main focus was on analyzing the change in compressive strength at 28 days and assessing the specific surface area of the resulting mixtures. The summarized data, reflecting the influence of chemical activation on the physical and mechanical properties of the samples compared to the control compositions, are presented in Table 2.

Table 2 shows the strength gain kinetics for the chemically activated fly ash.

Table 2
Summary Table of Results of Chemically Activated Fly Ash

№	Fly Ash, (%)	Type of activation	Activation parameter	S_{area} (cm^2/g)	R_{liq} 28 days, (MPa)	Increase over PC Control (35,0 MPa), %
Control Formulations:						
1	0 (PC)	Нет	–	3002	35,0	0,0
2	15 (FA)	Нет	0 min / 0%	3196	28,0	-20,0
CA: C_{act}=2 %			2% NaOH	3175		
1	5	CA	2% NaOH	3182	32,0	-8,6
2	15	CA	2% NaOH	3180	32,0	-8,6
3	30	CA	2% NaOH	3189	29,5	-15,7
CA: C_{act}=4% (optimum)		4% NaOH	3200			
4	5	CA	4% NaOH	3192	33,5	-4,3
5	15	CA	4% NaOH	3200	34,5	-1,4
6	25	CA	4% NaOH	3186	32,5	-7,1
7	30	CA	4% NaOH	3192	31,0	-11,4
CA: C_{act}=6%			6% NaOH	3201		
8	5	CA	6% NaOH	3200	33,0	-5,7
9	15	CA	6% NaOH	3202	33,5	-4,3
10	30	CA	6% NaOH	3199	30,0	-14,3
CA: Dosages 10%, 20% at C_{act}=4%						
11	10	CA	4% NaOH	3198	34,0	-2,9
12	20	CA	4% NaOH	3200	33,0	-5,7

The effect of chemical activation (CA) (adding NaOH to the unactivated FA) accelerates the reactions and influences early strength gain. Chemical activation, which does not change the specific surface area (it remains at 3200 cm/g), but stimulates the dissolution of active components, proved to be even slightly more effective, reaching a strength of 34.5 MPa with 4% NaOH and 15% CA provides a more complete utilization of the chemical potential of the fly ash in optimal activation regimes. In both cases, at fly ash dosages above 20%, the activation efficiency decreases, as there is insufficient calcium hydroxide released from the Portland cement to support a full pozzolanic reaction.

The concentration of sodium hydroxide used for the chemically activated fly ash is a critical factor determining the strength of the cement-ash composite.

Figure 1 shows the relationship between compressive strength (MPa) and admixture concentration (%)

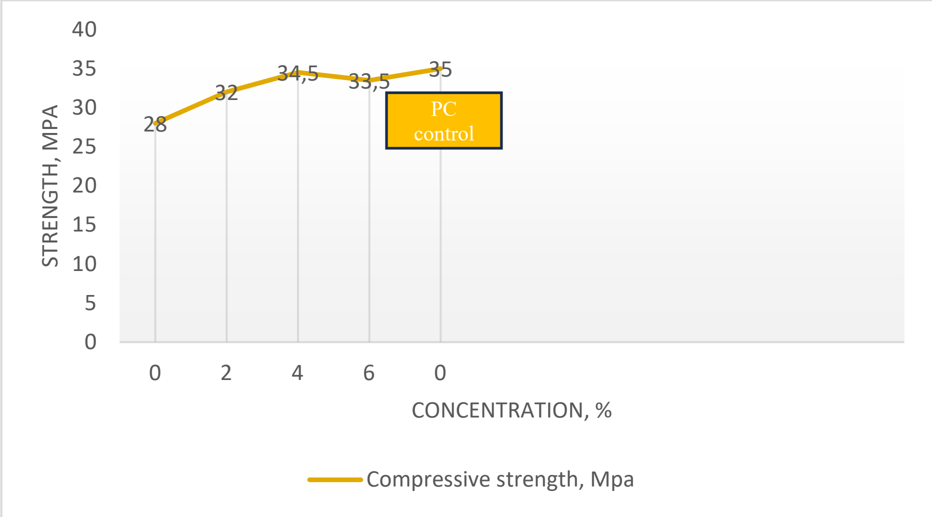

Figure 1 - Influence of chemically activating agent concentration (NaOH) (author's material)

The X-axis represents the admixture concentration (%), and the Y-axis represents the compressive strength (MPa). A separate "PC Control" is shown-a control sample of portland cement without admixture. The compressive strength is: 0%-28 MPa; 2% – 32 MPa; 4% – 34.5 MPa; 6% – 33.5 MPa; PC control – 35 MPa.

A significant increase in strength is observed as the concentration increases from 0% to 2%: +4 MPa (approximately +14.3% relative to the initial value)

At 4, the maximum value among the experimental compositions is reached-34.5 MPa, which is 6.5 MPa higher than the base composition (an increase of approximately 23%).

Further increasing to 6% causes a slight decrease in strength to 33.5 MPa, however, the value remains higher than at 0% and 2%.

The control sample (PC) shows 35 MPa–which is 0.5 MPa higher than the optimal experimental composition (4%).

Chemical activation, used to increase the activity of pozzolanic material, involves creating an alkaline environment that breaks down the stable aluminosilicate bonds in the ash structure. A low NaOH concentration does not provide a sufficient level of alkalinity for effectively dissolving the surface of the ash particles, leading to incomplete activation and, consequently, insufficient strength gain of the composite. According to, as the NaOH concentration increases, the rate of ash dissolution and the acceleration of the pozzolanic reaction with $Ca(OH)_2$ the reactivity of the cement increases, leading to a noticeable rise in strength. However, there is an optimal concentration: too high an alkali concentration can cause premature setting of the mixture, the formation of less durable phases, or even the crystallization of salts on the surface, which ultimately leads to a decrease or stagnation in the composite's strength. Thus, for each type of ash, the optimal NaOH concentration for achieving maximum strength must be determined experimentally.

Figure 2 is a micrograph of the original (unactivated) fly ash.The image demonstrates the characteristic morphology of this anthropogenic material, which is formed during coal combustion. Fly ash primarily consists of glassy, spherical particles known as ash microspheres (cenospheres,planespheres)

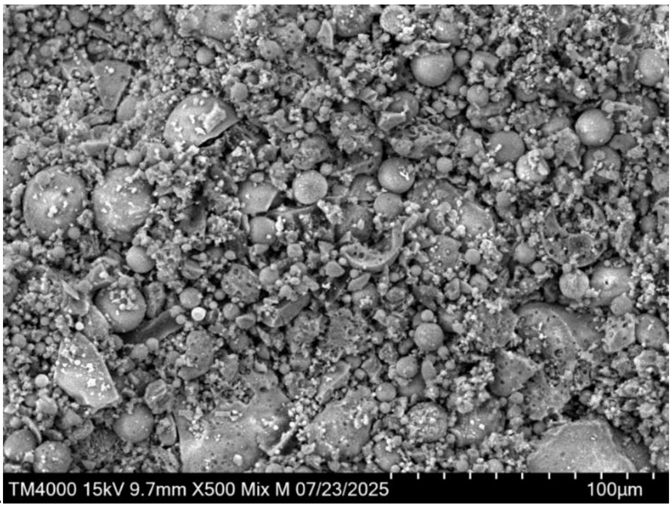

Figure 2 – Microstructure of unactivated fly ash (SEM, ×500) (author's material)

Figure 2 is a micrograph of the as-is (unactivated) fly ash obtained from coal combustion at thermal power plants.

The image demonstrates the characteristic morphology of this anthropogenic aluminosilicate material. The bulk of the ash consists of spherical particles of various diameters–from a few micrometers to ~80-100 um. Observed:

• Dense, glassy microspheres (planesphères) with a relatively smooth surface;
• Hollow spherical particles (cenospheres), which are characterized by low density;
• Agglomerated irregularly shaped particles;
• Fragments of broken spheres and a fine, dust-like fraction.

The spherical shape of the particles is due to the melting of the mineral part of the coal during combustion, followed by rapid cooling, during which the molten material takes the form of a droplet under the action of surface tension. The glassy structure indicates the predominance of the amorphous phase, which provides the material with potential pozzolanic activity.

The surface of most particles is relatively smooth, however, on individual microspheres, the following are observed:

• micropores,
• surface overgrowths,
• smaller particles adsorbed on the larger spheres.

The presence of particles of different sizes indicates the polydisperse nature of the material. The fine particles fill the intergranular space between the larger spheres, which can contribute to the microfilling effect in cementitious compositions.

The absence of distinct hydration products and damaged surfaces confirms that the ash is in its original, unactivated state.

The overall matrix structure is porous, with numerous pores and microcracks.

Figure 3 shows micrographs of the fly ash after chemically activating it for 28 days.

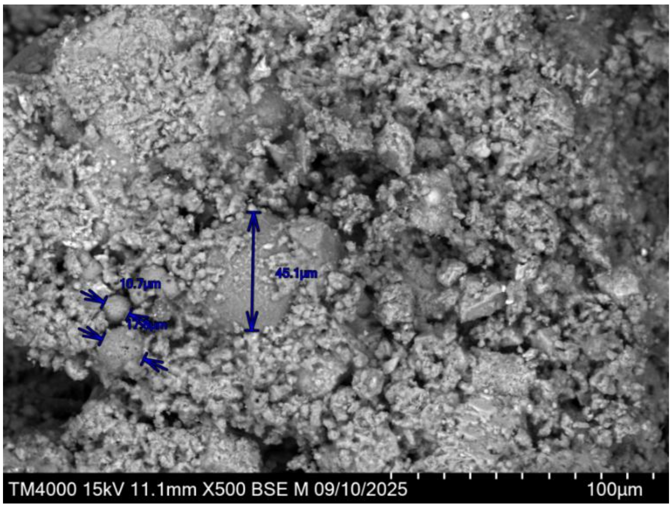

Figure 3 - Microscopic photographs of the fly ash after chemically activation (author's material)

Figure 3 shows the microstructure of the fly ash after chemically activating it. The image was captured using scanning electron microscopy (SEM) in backscattered electron (BSE) mode at x500 magnification (scale bar - 100 um).

In contrast to the initial (unactivated) ash, which is characterized by a predominance of intact glassy spheres, the activated sample exhibits pronounced structural changes:

- a significant number of shattered and partially deformed microspheres;
- the appearance of irregularly shaped fragmental particles;
- an increase in the proportion of the fine-dispersed fraction;
- formation of loose agglomerates;
- roughness and micropore structure of the particle surtace.

The image captures particles of approximately 7-11 um, as well as larger fragments of about 45 um, which indicates a redistribution of the particle size distribution due to chemical action.

The cement particles have an angular shape and are covered by a dense coating of setting gel.

This indicates destruction of the glassy layer under mechanical activation. The structure of the cement stone is very dense and uniform. Free $Ca(OH)_2$ crystals are present in minimal amounts. The C-A-S-H gels (flaky, indistinct morphology) and, likely, the N-A-S-H gels (dense, amorphous structures) are clearly visualized, having filled the pore space and securely bound all the solid particles

Figure 4 shows the microstructures of the cement samples after 28 days of hardening, obtained by scanning electron microscopy at x100 magnification. The study is aimed at evaluating the effect of chemically activating fly ash on the formation of the cement stone structure.

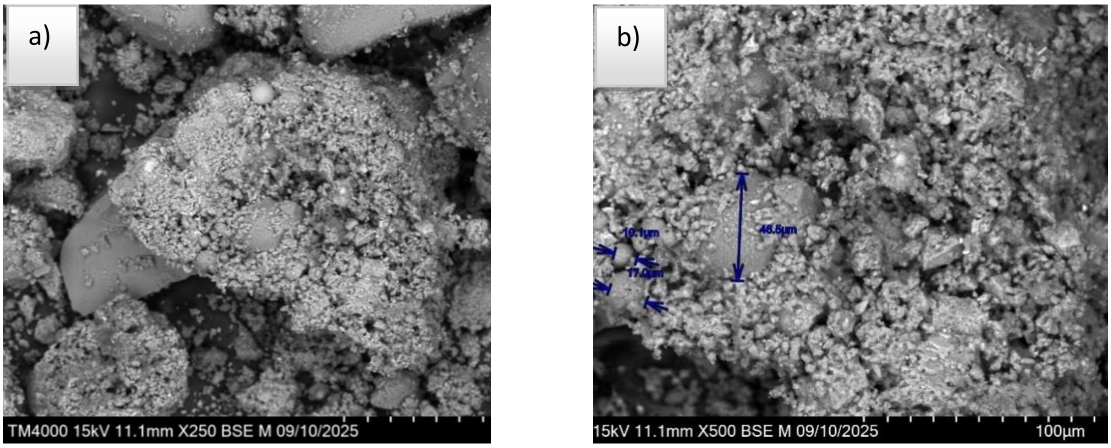

Figure 4 - Microscopic photographs of samples with activated fly ash: a) control sample 28 days (×100); chemically activated 28 days (×100) (author's material)

a) Control sample (28 days)

The microstructure of the control sample is characterized by:

- the presence of a dense matrix of hydration precipitates;
- presence of crystalline hydration phases;
- local pores and capillary voids;
- individual unreacted cement grains.

b) The structure shows the typical hydration products of Portland cement:

- gel-like formations (C-S-H phase),
- plate-like or prismatic crystals of calcium hydroxide,
- possible needle-like structures (etringite).

The structure is relatively dense, however, a certain porosity remains, which may limit further strength gain.

In the sample with chemically activated fly ash, pronounced structural differences are observed:

- a more homogeneous and denser matrix;
- reduction in the size and number of capillary pores;
- filling of the intergranular space with fine-dispersed particles;
- a more uniform distribution of hydration products.

The activated fly ash participates in the pozzolanic reaction by interacting with calcium hydroxide to form additional low-basic calcium silicates (C-S-H). As a result:

- reduces the amount of free $Ca(OH)_2$;
- increases the density of the structure;
- improved contact between particles;

¡ a more compact cement stone is formed.

4) The structure appears more monolithic compared to the control sample, which is consistent with the increase in strength characteristics obtained from mechanical testing.

The results of the microstructural analysis show that the introduction of chemically activated fly ash promotes the formation of a denser and more uniform cement stone structure by 28 days of curing, which leads to an increase in the material's performance and strength characteristics.

4 CONCLUSIONS

The study of the chemically activated (CA) fly ash on the properties of cement-ash composites demonstrated the high efficiency of the combined approach and confirmed its technical and economic feasibility.

The main conclusions and achievements are as follows:

1. It was determined that the critical factor determining the strength of the cement-ash composite is the concentration of sodium hydroxide. The optimal dosage for Ekibastuz coal fly ash is 4% NaOH. Under this regime, the strength of the mix with 15% ash content reached 34.5 MPa, which is as close as possible to the values of the reference sample on pure Portland cement (35.0 MPa).

2. It has been proven that the addition of NaOH creates an aggressive alkaline environment that breaks down stable aluminosilicate bonds and the glassy shell of ash microspheres. This stimulates the dissolution of active components and accelerates the pozzolanic reaction with the lime released during cement hydration.

3. It has been found that as the fly ash content exceeds 20%, the activation efficiency decreases. This is attributed to a deficiency of calcium hydroxide Ca(OH)2 in the system, which is necessary for the formation of secondary hydrate products.

4. Electron microscopy data confirmed a fundamental transformation of the matrix:

- In the unactivated compositions, a loose structure is observed, with an abundance of smooth cenospheres and large portlandite crystals.

- In the activated mixtures, the formation of a dense, homogeneous matrix was observed, where the pores and voids are filled with C-A-S-H and N-A-S-H gels that reliably bind the filler particles.

5. Chemical activation enables the efficient use of anthropogenic waste from the Ekibastuz Energy Complex in the production of building materials (in particular, hyper-pressed brick). This provides significant cement savings and addresses the region's pressing environmental issues without compromising the quality characteristics of the finished product.

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