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RESEARCH ARTICLE

CHANGES IN PROPERTIES OF PORTLAND CEMENTS CEM I 32.5 AND CEM I 42.5 WITH THE ADDITION OF FLY ASH)

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Abstract. *The fly ash derived from Ekibastuz HEPS-2 has a unique combination of physical and chemical properties, making it a highly suitable mineral additive for use in the production of Portland cement CEM II/A-Z. Its specific surface area of 290 m²/kg ensures a high degree of fineness, which is essential for achieving optimal particle packing and promoting efficient hydration reactions when mixed with cement. The true density of 2.1 g/cm³ indicates that the fly ash particles are relatively light yet dense enough to integrate well with cementitious materials. By mechanically blending carefully calculated proportions of Portland cement CEM I 32.5 or CEM I 42.5 with this fly ash, it is possible to achieve significant improvements in the performance and sustainability of the resulting CEM II/A-Z cement. The blending process takes into account the specific chemical properties of the fly ash, such as its pozzolanic activity, which refers to its ability to react with calcium hydroxide to form additional cementitious compounds. This reaction enhances the strength and durability of the cement over time, making it particularly advantageous for long-term applications in construction. Through precise mechanical blending with Portland cement CEM I 32.5 or CEM I 42.5, it is possible to achieve enhanced performance, improved sustainability, and cost efficiency, making it a valuable component in modern cement production.*

Keywords: *fly ash, cement, binder, water requirement, strength.*

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ҒЫЛЫМИ МАҚАЛА

КҮЛДІ ҚОСУ КЕЗІНДЕ ПОРТЛАНДЦЕМЕНТ ЦЕМ I 32,5 ЖӘНЕ ЦЕМ I 42,5 ҚАСИЕТТЕРІНІҢ ӨЗГЕРУІ

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Аңдатпа. *Екібастұз ГРЭС-2-де алынған күлдің физикалық және химиялық қасиеттерінің бірегей үйлесімі бар, бұл оны ЦЕМ II/А-Ш портландцемент өндірісінде қолдануға өте қолайлы минералды қоспаға айналдырады. Оның 290 м²/кг меншікті бетінің ауданы бөлшектердің оңтайлы орамасына қол жеткізу және цементпен араласқанда тиімді гидратация реакцияларына жәрдемдесу үшін қажет жоғары жұқалықты қамтамасыз етеді. Шынайы тығыздық 2,1 г/см³ болғандықтан күл бөлшектері жеңіл, сол себепті цементті материалдарға қосқанда гидратация реакциясына жақсы әсер етеді. ЦЕМ I 32.5 немесе ЦЕМ I 42.5 портландцементінің мұқият есептелген пропорцияларын күлмен механикалық араластыру нәтижесінде алынған ЦЕМ II/А-Ш цементінің өнімділігі мен тұрақтылығын айтарлықтай жақсартуға мүмкіндік береді. Араластыру процесі барысында күлдің ерекше химиялық қасиеттері, мысалы, оның пуццоландық белсенділігі ескеріледі, бұл оның қосымша цементті қосылыстар түзу үшін кальций гидроксидімен әрекеттесу қабілетін білдіреді. Бұл реакция уақыт өте келе цементтің беріктігі мен ұзақ мерзімділігін арттырады, бұл оны әсіресе ұзақ мерзімді құрылыс қолданбалары үшін пайдалы етеді. ЦЕМ I 32.5 немесе ЦЕМ I 42.5 портландцементімен механикалық түрде күлді дұрыс араластыру арқылы ол жақсартылған өнімділікке, экологиялық тазалыққа және үнемділікке қол жеткізе алады, бұл оны заманауи цемент өндірісіндегі құнды құрамдас етеді.*

Түйін сөздер: *күл, цемент, байланыстырғыш, су қажеттілігі, беріктік*

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НАУЧНАЯ СТАТЬЯ

ИЗМЕНЕНИЕ СВОЙСТВ ПОРТЛАНДЦЕМЕНТОВ ЦЕМ I 32,5 И ЦЕМ I 42,5 ПРИ ДОБАВЛЕНИИ ЗОЛЫ-УНОСА

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Аннотация. Зола-унос, полученная от Экибастузской ГРЭС-2, обладает уникальным сочетанием физических и химических свойств, что делает её весьма подходящей минеральной добавкой для производства портландцемента марки ЦЕМ II/А-Ш. Её удельная поверхность составляет 290 м²/кг, что обеспечивает высокую степень тонкости помола — важный фактор для оптимальной упаковки частиц и эффективного протекания гидратационных реакций при смешивании с цементом. Истинная плотность золы, равная 2,1 г/см³, указывает на то, что частицы достаточно лёгкие, но при этом достаточно плотные для хорошей интеграции с цементными материалами. Путём механического смешивания точно рассчитанных пропорций портландцемента ЦЕМ I 32.5 или ЦЕМ I 42.5 с данной золой возможно добиться значительного повышения эксплуатационных характеристик и экологичности получаемого цемента марки ЦЕМ II/А-Ш. При смешивании учитываются специфические химические свойства золы, в частности пуццолановая активность — способность реагировать с гидроксидом кальция с образованием дополнительных цементирующих соединений. Эта реакция способствует повышению прочности и долговечности цемента с течением времени, что особенно важно для долгосрочных строительных проектов. Точное механическое смешивание с портландцементом ЦЕМ I 32.5 или ЦЕМ I 42.5 позволяет добиться улучшенных эксплуатационных показателей, повышения устойчивости и экономической эффективности, делая золу-унос ценным компонентом современного цементного производства.

Ключевые слова: зола-унос, цемент, вяжущее, водопотребность, прочность.

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

АЛҒЫС

Бұл зерттеу жұмысы З.А. Естемесов Құрылыс материалдарын сертификаттау сынау орталық зертханасында. Авторлар университетке және зертханалық топқа баға жетпес басшылығы, мүмкіндіктері және зерттеу барысында қолдау көрсеткені үшін шексіз алғысын білдіреді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

БЛАГОДАРНОСТИ

Данное исследование проводилось под руководством З.А. Естемесова в Центральной лаборатории сертификационных испытаний строительных материалов. Авторы выражают глубокую благодарность университету и команде лаборатории за неоценимое руководство, оснащение и поддержку на протяжении всего исследования.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

1 INTRODUCTION

One of the major environmental challenges in Kazakhstan is the accumulation of fly ash and ash dumps from thermal power plants (TPPs). These volumes are increasing annually and are expected to reach 1 billion tons in the coming years. Globally, the problem is growing faster, as countries like China and India generate thermal energy by burning coal in TPP boilers **(Kurgankina 2019)**.

Over 300 technologies for utilizing fly ash can produce various materials such as aluminum, iron, silica, rare metals, white carbon black, and many others. However, the construction and road industries are the largest fly ash consumers, accounting for over 80% of global fly ash usage **(Derepko 2015)**.

One of the most promising applications of fly ash is as an additive in cement types CEM II and CEM V, where its content can range from 6–35% and 18–49% by mass, respectively, as specified by GOST government standard 31108-2020 "Common Construction Cements. Technical Requirements" **(Government standard 31108-2020)**. In this context, studying the changes in the properties of Portland cement with fly ash additives is highly relevant.

Purpose and Object of the Study

This study aims to examine the specific effects of fly ash on the properties of Portland cement CEM I 32.5 and CEM I 42.5.

- Object of the study: Fly ash from Ekibastuz HEPS-2.
- Subject of the study: Physicochemical and physico-mechanical properties of CEM I cements with the addition of fly ash.

2 LITERATURE REVIEW

About 5-7 million tons of fly ash waste are generated annually in Kazakhstan. These wastes are mainly formed in the process of coal combustion at TPPs, SDPPs and industrial boilers **(Maikonov 2023)**. At present 100 million tons of fly ash waste are accumulated in the country, in some estimates one can find figures of several billion tons, if we take into account the accumulated waste for the whole period of operation of coal-fired TPPs **(Zhanikulov 2023)**. These wastes represent a significant environmental problem, as they occupy large storage areas and can have harmful effects on the environment if not properly disposed of. However, they also represent a valuable raw material that can be utilized for various purposes such as the production of Portland cement, building materials or other industrial additives, thus improving the load resistance as well as solving the disposal problem **(Reis 2021)**.

The use of fly ash as an additive in the production of Portland cement has several important advantages and can improve the properties of the final product **(Chen 2010)**. Fly ash is a by-product of coal combustion that often contains calcium, silicon, aluminum, and iron oxides, making it potentially useful in the cement industry **(Klassen 2024)**.

The chemical composition of fly ash contains oxides of calcium (CaO), silicon (SiO_2), aluminum (Al_2O_3) and other components that are active in reaction with calcium hydroxide ($Ca(OH)_2$) formed during cement hydration. In particular, silicon and aluminum in fly ash can stimulate the formation of calcium silicates, which are the main components that determine the strength characteristics of cement.

Fly ash can be used as an active additive in the production of Portland cement to improve its hydraulic properties. The active components of fly ash (e.g., SiO_2 and Al_2O_3) react with calcium hydroxide during hydration to improve the strength and durability of the material. This promotes the formation of additional silicate and aluminocalcium phases that improve the mechanical properties of cement **(Taimasov 2015)**.

Effect on thermodynamic processes. When fly ash is added to the raw mix for Portland cement firing, changes in thermodynamic processes may occur:

- Reduction of firing temperature: Fly ash can reduce the melting point of the mixture and optimize the firing process, improving the energy efficiency of production.
- Formation of new phases: New calcium-silicate and aluminosilicate phases can be formed during the firing process with the addition of fly ash, which improve the durability and strength of cement.

Advantages of using fly ash:

- Improved cement strength: Mixing fly ash promotes the formation of additional active phases such as calcium silicate (C-S-H), which improves the strength characteristics of cement, especially in the later stages of curing.
- Reduced raw material costs: Fly ash is a by-product that can be used instead of some of the traditional input materials (e.g. clay and limestone), thus reducing the cost of cement production.
- Environmental benefits: The use of fly ash promotes the utilization of coal industry waste, which reduces the amount of waste and the negative impact on the environment.
- Reduction in CO_2 emissions: Fly ash can reduce the amount of clinker required for cement production as it can partially replace it in the raw material mix. This helps to reduce the carbon dioxide emissions that are generated during the cement clinker firing process **(Green economy 2013)**.

Potential problems and limitations:

- Low fly ash activity: Fly ash may not always be active enough to have a significant effect on improving cement properties if it has not been pretreated.
- Change in cement properties: Excessive addition of fly ash can lead to a reduction in early cement strength as it can slow down the hydration process and increase curing time.

The use of fly ash as an additive in Portland cement production has many advantages including improved cement strength, reduced environmental impact and savings on raw materials. However, it is important to properly dose the fly ash into the raw material mixture as excessive amounts can adversely affect the properties of cement **(Zhanikulov 2022)**.

Thai researchers Panumas Saingam et al. **(Panumas 2024)** investigated the production of self-compacting concrete using bulk fly ash and calcined calcium carbonate with Portland cement. Various experimental data such as workability, mechanical properties, durability and microstructural characteristics were obtained. The results of the workability tests showed that all mixtures met satisfactory conditions in terms of flow times ranging from 2.50 to 4.55 seconds and cone settlement values ranging from 650 to 800 mm. The optimum compressive strength is 73.8 MPa at 91 days, which is 7.7% higher than that of the control group. The high replacement ratio, up to 20% fly ash, provided a compressive strength of 58.9 MPa at 91 days. This clearly shows the prospect of significantly reducing cement consumption while maintaining structural integrity. These results indicate the possibility of reducing cement consumption in concrete production, which again defines low carbon emissions and waste management in line with international Sustainable Development Goals.

Belgian scientists Shiju Joseph et al. **(Shiju, 2019)** studied Portland cement by blending with large amount of fly ash and using Na_2SO_4. Increasing the rate of replacement of Portland cement clinker with additional cementitious materials such as fly ash, strategies to reduce the environmental impact of cement and concrete industries. Although fly ash is widely available, especially in developing countries where most construction activities are projected to take place in the near future, in practice replacement rates are limited to about 25-30% due to its low reactivity. This paper studies the effect of sodium sulfate on the activation of Portland cement mixed with 50% by weight of class F fly ash. Activation of Na_2SO_4 with fly ash promotes a significant increase in strength at both early and later ages.

Erik Stoltenberg-Hansson **(Erik Stoltenberg-Hansson 2011)** was tested with class F fly ash used to produce cement with 20% fly ash. Unground and ground fly ash were mixed with reference Portland cement of high fineness and tested for strength in mortar (ISO/CEN method). The fly ash was also tested for chemical composition, bulk density and specific gravity, fineness (Blaine) and particle size distribution (laser method). There is considerable variation in the specific gravity of the delivered fly ash. It is shown that even a small amount of grinding significantly increases the specific gravity and improves and homogenizes the particle size distribution, resulting in higher strength. The increase in strength corresponds to a decrease in air void content. Grinding fly ash and clinker together in large scale mills reduces energy consumption, providing the same strength after 28 days as mixed cement with fly ash with higher fineness.

3 MATERIALS AND METHODS

The binders used in this study were Portland cement of grades CEM I 32.5 and CEM I 42.5 A comparative analysis of the physico-mechanical properties and chemical characteristics of these cements was conducted, based on the technical requirements outlined in government standard 31108-2020. The comparison, shown in Tables 2–5, demonstrates that the properties of these cements meet the regulatory standards. Thus, they can be effectively used as a benchmark for evaluating the suitability of fly ash as an additive for cements grade CEM I.

Table 1
Phase Composition of CEM I cement types

Phases	**Compositions (%)**	
	CEM I 32.5	**CEM I 42.5**
Alite ($3CaO{\cdot}SiO_2$, C_3S)	55.3	63.7
Belite ($2CaO{\cdot}SiO_2$, C_2S)	18.8	10.4
Aluminate ($3CaO{\cdot}Al_2O_3$, C_3A)	3.8	5.1
Ferrite ($4CaO{\cdot}Al_2O_3{\cdot}Fe_2O_3$, C_4AF)	12.7	11.4
Gypsum ($CaSO_4{\cdot}2H_2O$)	6.8	6.2

Table 2
Comparative Data on Physico-Mechanical Properties of Standard Requirements and Cement CEM I 32.5
(Note: If data from Table 1 needs to be included, please provide the table content or structure.)

Indicator Name	**Unit of Measurement**	**Test Method Standard**	**Standard Requirement**	**Actual Value**	**Note**
Fineness by passage through the sieve No. 008	%	government standard 30744-2001, Section 5.1	Not standardized	97.0	
Normal consistency	%	government standard 30744-2001, Section 6.2.1	Not standardized	27.5	
Initial setting time	minutes	government standard 30744-2001, Section 6.2.2	Not earlier than 75	210	
Volume stability (expansion)	mm	government standard 30744-2001, Section 7	Not more than 10	No changes	
Compressive strength at 7 days	MPa	government standard 30744-2001, Section 8.2	Not less than 16	17.0	
Compressive strength at 28 days	MPa	government standard 30744-2001, Section 8.2	Minimum value 32.5 Maximum value 52.5	41.0	

Compressive strength after heat treatment	MPa	government standard 30744-2001, Section 8.2	More than 25.5	28.0	Group I effectiveness for CEM I
The specific effective activity of natural radionuclides	Bq/kg	government standard 30108-94, Appendix A	Up to 370	103.1	

Table 3
Comparative Data on Chemical Indicators of the Standard Requirement and Cement CEM I 32.5

Determined Characteristics	Units of Measurement	Standard Requirement	Actual Test Values	Test Method Standard	Uncertainty
Loss on ignition	%	Not more than 5.0	2.34	government standard 5382-2019, Section 7	–
Mass fraction of insoluble residue	%	Not more than 5.0	1.96	government standard 5382-2019, Section 8	–
Sulfur (VI) oxide content	%	Not more than 3.5	1.42	government standard 5382-2019, Section 14	–
Mass fraction of magnesium oxide	%	Not more than 5.0	1.14	government standard 5382-2019, Section 10	–
Chloride ion content	%	Not more than 0.10	0.018	government standard 5382-2019, Section 21	–

Table 4
Comparative Data on Physico-Mechanical Properties of the Standard Requirement and Cement CEM I 42.5

Indicator Name	Unit of Measurement	Test Method Standard	Standard Requirement	Actual Value	Note
Fineness by passage through the sieve No. 008	%	government standard 30744-2001, Section 5.1	Not standardized	97.4	
Normal consistency	%	government standard 30744-2001, Section 6.2.1	Not standardized	28.0	
Initial setting time	minutes	government standard 30744-2001, Section 6.2.2	Not earlier than 60	220	
Volume stability (expansion)	mm	government standard 30744-2001, Section 7	Not more than 10	No changes	
Compressive strength at 7 days	MPa	government standard 30744-2001, Section 8.2	Not less than 10	29.7	
Compressive strength at 28 days	MPa	government standard 30744-2001, Section 8.2	Minimum value 42.5 Maximum value 62.5	45.3	
Compressive strength after heat treatment	MPa	government standard 30744-2001, Section 8.2	More than 27.0	29.3	Group I effectiveness for CEM I
The specific effective activity of natural radionuclides	Bq/kg	government standard 30108-94, Appendix A	Up to 370	100.7	

Table 5
Comparative Data on Chemical Indicators of the Standard Requirement and Cement CEM I 42.5

Determined Characteristics	Units of Measurement	Standard Requirement	Actual Test Values	Test Method Standard	Uncertainty
Loss on ignition	%	Not more than 5.0	2.51	government standard 5382-2019, Section 7	–

Mass fraction of insoluble residue	%	Not more than 5.0	1.87	government standard 5382-2019, Section 8	–
Sulfur (VI) oxide content	%	Not more than 3.5	1.85	government standard 5382-2019, Section 14	–
Mass fraction of magnesium oxide	%	Not more than 5.0	1.11	government standard 5382-2019, Section 10	–
Chloride ion content	%	Not more than 0.10	0.035	government standard 5382-2019, Section 21	–

The fly ash from Ekibastuz HEPS-2 was used as a mineral additive with the following chemical and mineralogical characteristics (Tables 6-8).

Table 6
Chemical composition (%)

Component	SiO_2	Al_2O_3	(Fe_2O_3+FeO)	CaO	MgO	SO_3	K_2O	Na_2O	Unspecified (loss on ignition)
Percentage (%)	56.7	28.6	6.4	1.1	0.35	1.3	0.03	0.52	3.0

Table 7
The phase composition (%, rounded):

Mineral Phase	Mullite ($3Al_2O_3{\cdot}SiO_2$)	α-quartz (SiO_2)	Sillimanite ($Al_2O_3{\cdot}SiO_2$)	Hematite (Fe_2O_3)	Glass phase	Unburned carbon
Percentage (%)	38	32	12	5	10	3

Table 8
Grain size distribution of ash particles (%):

Grain Size (mm)	Particles up to 0.5 mm	0.45 mm	0.25 mm	0.1 mm	0.09 mm	0.08 mm	0.06 mm	0.05 mm	0.045 mm	0.04 mm
Distribution (%)	0.14	2.26	3.6	25.8	0.84	12.12	4.5	21.46	21.38	7.9

Unburned carbon is mostly found in larger particles, while the glass phase is in smaller particles. The minerals are evenly distributed across all fractions.

Activity modulus: Basic modulus (CaO+MgO) /(SiO_2+Al_2O_3) ≈ 0.02, and the hydraulic activity modulus (CaO+Al_2O_3+MgO) /(SiO_2+ TiO_2) is 0.53. This indicates that the fly ash is highly acidic and thus it has low activity.

Specific surface area – 290 m^2/kg;

True density – 2.1 g/cm^3;

Bulk density – 780 kg/m^3.

As seen from Table 9, fly ash can be used as a mineral additive for CEM I and CEM V cement types, based on its chemical characteristics.

Table 9
Comparative Data of Chemical Indicators of the Standard Requirement and Fly Ash

Indicator Name	**Units of Measurement**	**Testing Standard**	**Standard Norm according to government standard 31108-2020**	**Actual Value of Fly Ash**
Alkali oxide content (R_2O) calculated as Na_2O	%	government standard 5382-2019, Section 12	Not more than 2.0	0.54
MgO content	%	government standard 5382-2019, Section 7.3	Not more than 5.0	0.35
Loss of mass upon calcination (ppp)	%	government standard 5382-2019, Section 4	Not more than 5.0	3.0
Volume uniformity (cement expansion with fly ash addition)	mm	government standard 30744-2001, Section 7	Not more than 10	9.0
Reactive SiO_2 content	%	government standard 5382-2019, Section 6; (X-ray fluorescence analysis)	No less than 25	26

Mass fraction of reactive CaO	%	government standard 5382-2019, Section 7	Not more than 10	0.5
Mass fraction of free calcium oxide CaO	%	government standard 5382-2019, Section 13	Not more than 1	Absent
The specific effective activity of natural radionuclides	Bq/kg	government standard 30108-94	Up to 370	72

The phase composition of cement and fly ash was determined using the modernized DRON-3M diffractometer with CuKα radiation, along with accompanying software. X-ray diffraction patterns were obtained in the 2θ angle range from 10 to 70º. The chemical composition of the fly ash was determined using the energy-dispersive X-ray fluorescence spectrometer EDX-8000.

The physical-mechanical properties of cement and fly ash were determined by the technical requirements of government standard 30744-2001 **(Government Standard 2001)** and government standard 8736-2014 **(Government Standard 2014)**. The specific effective activity of radionucides was measured following government standard 30108-94 **(Government standard 1994)**.

The effect of fly ash contents on the strength of Portland cement CEM I was determined using samples with dimensions of 2x2x2 cm, made from a mixture with normal consistency. The samples were steam-cured at 90ºC following a 3+10+3 hour schedule (rise + isotherm + fall).

The strength of the samples was tested after one day of autoclave curing. The strength of the autoclaved samples after water storage was tested in 7, 14, and 28 days. The fly ash content in the binder composition was 5%, 10%, 15%, and 20% by weight.

The compressive strength of the samples was tested using the hydraulic press with software, which allowed the obtained data to indicate their grade strength.

3 RESULTS AND DISCUSSION

Table 10 shows the influence of the fly ash content on the normal consistency and setting times of Portland cement CEM I 42.5, from which the following can be concluded:

- Fly ash increases the water demand for cement, the higher the ash content, the greater the increase in water demand. For example, the normal consistency of pure cement is 28.5%, but adding 5%, 10%, and 15% fly ash rises to 29.5%, 30.5%, and 31.5%, respectively. As a result, under the same conditions, the strength of hardened fly ash-containing cement will be lower during the early setting periods compared to cement without ash. This is because the increased water content raises the porosity of the cement paste, which in this case reduces its density and strength.
- Fly ash delays both the initial and final setting times of cement, and the higher the content, the more the setting times are delayed in the fly ash-cement paste. For example, the initial and final setting times of pure cement paste are 165 and 200 minutes, respectively. While with the addition of 15% ash, they reach 205 and 250 minutes, respectively.
- The fly ash from the Ekibastuz HEPS-2 increases the water demand of Portland cement CEM I 42.5 and delays the setting times of the cement paste.
- Based on this, it can be inferred that ultra-acidic fly ashes, (e.g. fly ashes from Ekibastuz coal), generally possess these properties in the cement-fly ash-ultra-acidic-water system.

Table 10
Influence of fly ash content on normal consistency and setting times of cement paste

Sample No.	Cement CEM I 42.5 N (%)	Fly Ash (%)	Normal Consistency of Cement Paste (%)	Setting Times (hour-minute):	
				start	end
1	100	0	28.5	165	210
2	95	5	29.5	180	230
3	90	10	30.5	190	240
4	85	15	31.5	205	250

The increased water demand for fly ash-containing cement, which also causes a delay in the setting times of the cement, can be attributed to the following factors:

- The presence of unburned carbon (coke) in the fly ash, which has a high-water demand (up to 50%);
- The abundance of hollow particles in the fly ash, which absorb additional water due to their porous structure.

Table 11 provides data on the strength change of autoclaved samples:

- Without the addition of fly ash.
- With fly ash added in the range of 5-20% by mass.
- The strength of cement and fly ash-cement stone after one day of curing under hydrothermal conditions and after 7, 14, and 28 days of further curing in water.

The following can be concluded based on the strength synthesis data of cement and fly ash-cement stone:

- Pure cement stones achieve standard strengths of 45.7 MPa after one day of hydrothermal treatment and 53.3 MPa after 28 days of curing in water. Hydrothermal treatment significantly enhances their strength compared to natural curing conditions.
- Fly ash-cement stones exhibit lower strength than pure cement stones even after undergoing hydrothermal treatment and 28 days of curing.
- Furthermore, as the fly ash content in the binder increases, its negative impact on the strength of the fly ash-cement stone becomes more pronounced.
- However, the rate of strength gain in fly ash-cement stone surpasses that of pure cement stone. For instance, the strength of pure cement stone made from CEM I 42.5 is 46.5 MPa after one day of hydrothermal treatment and increases to 53.3 MPa after 28 days of water curing, showing a gain of 6.8 MPa. In contrast, cement stone with a 5% fly ash addition has strength values of 33.8 MPa and 45.3 MPa, with a gain of 11.5 MPa over the same period. These results suggest that at 90 days and even at 360 days the strength of fly ash-cement stone will likely exceed that of pure cement stone.

Table 11

Influence of fly ash content on the strength of autoclaved cement stone

Binder Composition (%)			**Strength of autoclaved samples (MPa)**				
Cement		**Fly ash**	**Age of Specimen (days)**				**The difference in strength between 1 and 28 days of curing**
CEM I 32.5	**CEM I 42.5**		**1**	**7**	**14**	**28***	
100	−	−	36,0	42,7	43,4	45,7	9,7
−	100	−	46,5	47,8	49,5	53,3	6,8
95	−	5	33,8	38,3	41,3	45,3	11,5
90	−	10	30,5	35,4	38,9	42,4	11,9
85	−	15	28,7	33,3	37,5	40,8	12,1
80	−	2,0	25,6	29,8	33,8	38,3	12,7
−	95	5	36,7	45,5	47,8	48,7	42,0
−	90	10	33,8	43,7	45,5	46,5	12,7
−	85	15	32,3	40,8	43,8	44,8	12,5
−	80	20	32,0	39,8	41,7	43,5	11,5

Note: Some of the samples will continue curing in a water environment. Testing will be conducted after 90, 180, and 360 days.

This trend, where cement stone with ash shows relatively low strength at early ages but has the potential for greater long-term strength development, has been previously observed by the authors of studies. It can be attributed to the following combined factors:

- The relatively low strength at early ages is primarily attributed to the reduced cement content in the hardening system.
- The prolonged strength development in ash-containing hardened systems is attributed to the active participation of fly ash components in the hydration process. These components include:
- Glass-crystalline particles serve as nuclei for the crystallization of new phases.

- The glass phase possessing pozzolanic and hydraulic properties, interacts with lime, reducing its content in the hardening system and forming additional cementing substances.
- The reactive surface of silica, which reacts with lime and other new aqueous compounds to create a strong contact zone.
- These physicochemical processes collectively enhance the long-term strength of the ash-cement-water system.

4 CONCLUSIONS

According to chemical indicators, the fly ash from Ekibastuz HEPS-2 meets the technical requirements of government standard 25818-2017 and government standard 31108-2020 as a mineral additive for Portland cement CEM II.

Despite its significantly higher growth rate (approximately 11-12 MPa compared to 7-10 MPa for pure cement), the strength of fly ash-cement stone during the early stages of hardening remains lower than that of pure cement stone. This is primarily due to the highly acidic nature of fly ash and its low glass phase content (10%).

The study of Portland cements CEM I 32.5 and CEM I 42.5 with the addition of fly ash has demonstrated significant changes in their physical and mechanical properties. The incorporation of fly ash influences the hydration process, leading to modifications in setting time, compressive strength, and overall durability.

Additional mechanochemical technological treatments are strongly recommended to increase the activity of acidic fly ashes, and the authors of this article are currently working on these methods.

Overall, the use of fly ash as a supplementary cementitious material offers economic and environmental benefits by reducing clinker consumption and lowering CO_2 emissions. The optimal dosage of fly ash should be carefully considered to balance strength development and durability requirements for specific construction applications. Future research should focus on optimizing fly ash content and evaluating its effects under various curing conditions and environmental exposures.

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