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RESEARCH ARTICLE

THE EFFECT OF ASH AND SLAG WASTE ON THE PROPERTIES OF CEMENT FOR THE PRODUCTION OF POLYSTYRENE CONCRETE

A.S. Maikonov[1], Y.R. Krivoborodov[2], R.K. Niyazbekova[3], L.S. Shansharova[3,*], M.A. Serekpayeva[3]

[1]Kazakh-British Technical University, 050006, Almaty, Kazakhstan
[2]Moscow State University of Civil Engineering, 125047, Moscow, Russia
[3]S.Seifullin Kazakh Agrotechnical Research University, 010000, Astana, Kazakhstan

Abstract. *The annual accumulation of Coal Ash and Slag Waste (CASW) at TPP ash dumps poses a critical environmental challenge, particularly in Kazakhstan due to the high ash content (approximately 40%) of Ekibastuz coal. This yields millions of tonnes of waste on vast technogenic deposits. The problem is twofold: fly ash contaminates soil and groundwater with heavy metals, and water from hydro-ash removal systems (HARS) is a highly mineralized effluent requiring costly disposal. The low utilization rate necessitates the complex integration of solid and liquid waste components into industrial circulation as a strategic priority. This timely solution addresses the dual environmental problem, simultaneously reducing waste volumes and significantly decreasing the consumption of natural resources (cement and fresh water) in the construction industry. This article specifically investigates the feasibility of the integrated use of CASW derived from Ekibastuz coal: utilizing fly ash as a mineral admixture and employing water from HARS as the mixing water in the production of lightweight cellular concrete, namely polystyrene-foam concrete. The research is dedicated to studying the combined effect of these two components on the processes of structure formation and the resultant key physic and mechanical properties of the cement stone. To ensure the safety and characterize the raw materials, including the ash from the Ekibastuz Basin, the study utilized X-ray fluorescence analysis (XRF), X-ray diffraction analysis (XRD), and structural morphology assessment using a scanning electron microscope (SEM). The article presents the detailed findings on the physic and mechanical properties of the obtained composites, confirming their potential for safe and effective industrial application.*

Keywords: *polystyrene concrete, fly ash, standard consistency, setting time, compressive strength, hydration.*

***Corresponding author**
Lazzat Shansharova, e-mail: l.sarsenbayevna@gmail.com

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ҒЫЛЫМИ МАҚАЛА

ПОЛИСТИРОЛБЕТОН ӨНДІРІСІНДЕ КҮЛ-ҚОЖ ҚАЛДЫҚТАРЫНЫҢ ЦЕМЕНТ ҚАСИЕТТЕРІНЕ ӘСЕРІ

А.С. Майконов[1], Ю.Р. Кривобородов[2], Р.К. Ниязбекова[3], Л.С. Шаншарова[3,*], М.А. Серекпаева[3]

[1]Қазақстан-Британ техникалық университеті, 050006, Алматы, Қазақстан
[2]Мәскеу мемлекеттік құрылыс университеті, 125047, Мәскеу, Ресей
[3]С.Сейфуллин ат. Қазақ агротехникалық зерттеу университеті, 010000, Астана, Қазақстан

Аңдатпа. *Жылу электр станцияларының (ЖЭС) күл үйінділерінде жыл сайын күл-қож қалдықтарының (ККҚ) жинақталуы Қазақстан үшін өзекті экологиялық мәселе болып табылады, өйткені ЖЭС негізінен күлі көп (шамамен 40 %) Екібастұз көмірін жағады. Бұл кен орындарында ауқымды техногендік миллиондаған тонна қалдықтарының түзілуіне әкеп соқтырады. Аталған мәселе қос сипаттан тұрады: ұшпа күл топырақты және жерасты суларын ауыр металдармен ластайды, ал гидрокүлжою жүйелерінен (ГКЖ) шыққан су – қымбат кәдеге жаратуды қажет ететін, құрамында минералдары жоғары ағынды су болып табылады. Осы жанама өнімдерді пайдаланудың төмен деңгейі қатты және сұйық қалдық компоненттерін өнеркәсіптік айналымға кешенді тартуды стратегиялық басымдыққа айналдырады. Бұл уақтылы шешім қалдықтардың көлемін бір мезгілде азайта отырып, құрылыс секторындағы табиғи ресурстарды (цемент пен су) тұтынуды айтарлықтай төмендете отырып, қос экологиялық мәселені жояды. Бұл мақалада Екібастұз көмірін жағу нәтижесінде алынған ККҚ-ны кешенді пайдалану мүмкіндігі қарастырылады: ұшпа күлді минералды қоспа ретінде және ГКЖ-дан алынған суды жеңіл ұялы бетон, атап айтқанда пенополистиролбетон өндірісінде араластыру суы ретінде қолдану. Зерттеу осы екі компоненттің құрылым түзілу процестеріне және олар тудыратын цемент тасының негізгі физика-механикалық қасиеттеріне бірлескен әсерін зерттеуге арналған. Шикізат материалдарының, оның ішінде Екібастұз бассейні күлінің сипаттамаларының қауіпсіздігін қамтамасыз ету үшін рентгендік-флуоресценттік талдау, рентгендік-фазалық талдау (РФТ) және сканерлеуші электрондық микроскоп (СЭМ) арқылы құрылымдық морфологияны бағалау жүзеге асырылды. Мақалада алынған композиттердің қауіпсіз және тиімді өнеркәсіптік қолдану әлеуетін растайтын физика-механикалық қасиеттерін зерттеудің толық нәтижелері ұсынылған.*

Түйін сөздер: *полистиролбетон, ұшпа күл, қалыпты тығыздық, қатаю уақыты, қысу беріктігі, гидратация.*

***Автор-корреспондент**
Лаззат Шаншарова, e-mail: l.sarsenbayevna@gmail.com

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НАУЧНАЯ СТАТЬЯ

ВЛИЯНИЕ ЗОЛОШЛАКОВЫХ ОТХОДОВ НА СВОЙСТВА ЦЕМЕНТА ДЛЯ ПРОИЗВОДСТВА ПОЛИСТИРОЛБЕТОНА

А.С. Майконов[1], Ю.Р. Кривобородов[2], Р.К. Ниязбекова[3], Л.С. Шаншарова[3,*], М.А. Серекпаева[3]

[1]Казахстанско-Британский технический университет, 050006, Алматы, Казахстан
[2]Московский Государственный Строительный Университет, 125047, Москва, Россия
[3]Казахский агротехнический исследовательский университет им. С. Сейфуллина, 010000, Астана, Казахстан

Аннотация. *Ежегодное накопление золошлаковых отходов (ЗШО) на золоотвалах тепловых электростанций (ТЭС) представляет собой острую экологическую проблему, особенно актуальную для Казахстана, где ТЭС преимущественно сжигают экибастузский уголь с высокой зольностью (приблизительно 40%). Это приводит к образованию миллионов тонн отходов на обширных техногенных месторождениях. Проблема имеет двойственный характер: летучая зола загрязняет почву и грунтовые воды тяжелыми металлами, а вода из систем гидрозолоудаления (ГЗУ) является высокоминерализованным стоком, требующим дорогостоящей утилизации. Низкий уровень утилизации таких побочных продуктов делает комплексное вовлечение твердых и жидких компонентов отходов в промышленный оборот стратегическим приоритетом. Данное своевременное решение устраняет двойную экологическую проблему, одновременно сокращая объемы отходов и существенно снижая потребление природных ресурсов (цемента и пресной воды) в строительном секторе. В данной статье исследуется возможность комплексного использования ЗШО, полученных при сжигании экибастузского угля: использование летучей золы в качестве минеральной добавки и воды из ГЗУ в качестве воды затворения при производстве легкого ячеистого бетона, а именно пенополистиролбетона. Исследование посвящено изучению совместного влияния двух компонентов на процессы структурообразования и обусловленные ими ключевые физико-механические свойства цементного камня. Для обеспечения безопасности характеристик сырьевых материалов, включая золу Экибастузского бассейна, были применены рентгенофлуоресцентный анализ, рентгенофазовый анализ (РФА) и оценка структурной морфологии с использованием сканирующего электронного микроскопа (СЭМ). В статье представлены подробные результаты исследований физико-механических свойств полученных композитов, подтверждающие их потенциал для безопасного и эффективного промышленного применения.*

Ключевые слова: *полистиролбетон, летучая зола, нормальная густота, сроки схватывания, прочность на сжатие, гидратация.*

***Автор-корреспондент**
Лаззат Шаншарова, e-mail: l.sarsenbayevna@gmail.com

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

The authors declare that no generative artificial intelligence technologies or AI-based tools were used in the preparation of this 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.

Авторлар мақаланы дайындау барысында генеративті жасанды интеллект технологиялары мен жасанды интеллектке негізделген технологияларды пайдаланбағанын мәлімдейді.

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.

Авторы заявляют о том, что при подготовке статьи не использовались технологии генеративного искусственного интеллекта и технологии, основанные на искусственном интеллекте.

1 INTRODUCTION

Today, the construction industry relies on a variety of structural and thermal insulation materials. Among the most common are lightweight concretes, which include gas concrete, foam concrete, and polystyrene-foam concrete. However, these materials often suffer from high cost and certain limitations in their physic and mechanical properties (**Dvorkin et.al., 2022**).

A major degradation factor in polystyrene-foam concrete is the delamination between the cement paste and the polymer particles. Consequently, the use of effective aggregates, especially those that enhance the concrete's strength and structural integrity, plays a crucial role in product longevity. The development and implementation of new polystyrene-foam concrete compositions based on affordable, high-performing alternative aggregates is therefore of paramount environmental importance.

This need is compounded by the necessity of responsibly managing industrial waste. The problem of directional structuring using dispersed materials, along with the application of waste from Combined Heat and Power Plants (CHPPs) such as slags and sludge is highly relevant (**Khudyakova et.al., 2019**). Solving this challenge can significantly improve the properties of composite, multifunctional materials based on cements and polymers, eliminate the need for expensive chemical additives, increase structural strength, and crucially, reduce the cost of cements used in concrete production. In fact, utilizing industrial waste in construction minimizes the generation of primary waste, reduces the use of virgin resources, and boosts the overall sustainability of the construction industry. When selecting the composition for polystyrene-foam concrete, special attention must be paid to incorporating local raw materials, particularly man-made waste, the proper disposal of which directly contributes to environmental improvement.

Thus, the purpose of this article is the comprehensive investigation of polystyrene-foam concrete samples based on a cement binder utilizing the combined application of fly ash and water from hydro-ash removal systems (HARS). The research is aimed at studying the influence of these components on the processes of structure formation and the physic and mechanical properties of the composite, with the ultimate goal of achieving cement economy, improving concrete quality, and solving pressing environmental problems.

To achieve this goal, the following tasks must be solved:

- investigate the properties of the raw materials for the production of polystyrene-foam concrete samples.

- investigate the technological properties of the fresh polystyrene-foam concrete samples.

- investigate the patterns of changes in the hydration properties of the resulting hardened samples.

- the scientific novelty of the research in this article lies in the creation of polystyrene-foam concrete with the necessary functional properties based on the innovative use of fly ash and water from a hydro-ash removal channel (HARS water).

The practical significance of the research lies in developing a sustainable and cost-effective method for producing polystyrene-foam concrete through the complete utilization of both fly ash and HARS water.

This work directly addresses major environmental challenges associated with TPP waste by:

- providing a feasible technology for utilizing millions of tonnes of industrial waste;
- achieving significant cement savings and reducing the need for primary resources (fresh water);
- offering a scientifically validated composition for a multifunctional building material with improved physic and mechanical characteristics.

2 LITERATURE REVIEW

The study of the properties of concrete with hydraulic removal ash is devoted to foreign articles (**Yimam et.al., 2021; Luo et.al., 2021**). There are known works that are devoted to the study of the properties of concrete with the replacement of a part of cement with hydraulic removal ash (**Golewski, 2020; Srikanth et.al., 2021**).

The researchers confirmed that fly ash possesses the necessary pozzolanic properties for activation within the composition of the cement binder (**Zou et.al., 2020**). It was established that the coal ash and slag waste (CASW) from the combustion of Ekibastuz coal possesses the potential for use in the production of building materials due to its silica-alumina composition (**Thenepalli et.al., 2018**).

Looking into the ash and slag waste processing, a significant amount of research and development is carried out on their secondary processing for extraction of valuable components and production of construction materials (**Gao et.al., 2020**). The wastes produced by certain industries are valuable secondary raw materials, that are heat-treated, containing calcium and silicate components necessary for the production of binders and composite materials based on cements and polymers and represent both single-component and multi-component raw material. The quality of materials can be improved by strengthening the matrix with micro- and nanoparticles (**Khamit et.al., 2024; Syndarbekova et.al., 2025**).

Refering to the research by author (**Golewski, 2018**) on the possibility of utilization of industrial waste, the addition of fly ash from ash dumps to cement mix strengthens the structure as a result of the presence of microparticles in the ash and their positive effect on the properties of composite material. Depending on the material, the fractional composition of HARS, fly ash, addition of fly ash to cement can have different effects on the properties of the resulting material. Fly ash can affect the hydration and hardening of cement as well as the strength of the product. In some cases, fly ash increases the standard consistency and plasticity of cement batter, making it easier to handle during the construction period (**Takirova et.al., 2025; Abildaeva et.al., 2022**). The complex crystallization processes of cement play a crucial role in the strength of materials and the durability of the resulting material. The structure of the hydrated cement mass can influence the porosity, permeability and mechanical properties of concrete (**Niyazbekova et.al., 2023**).

Fly ash content influences the hydration and hardening processes of compositions, which are accelerated by heat and humidity treatment. In addition, as a result of the redistribution of volume changes with the addition of fly ash and water from the hydraulic ash trap channel, the cracking is reduced (**Bo et.al., 2021**).

In addition, replacement of ordinary water with water from ash removal facility of TPPs for cement batter production is a feasible solution to environmental and economic problems associated with the utilization of ash and slag waste. On one hand, the use of fly ash in concrete leads to saving of expensive Portland cement, as well as to the reduction of heat generation during concrete hardening, on the other hand - to a slower curing and strengthening of concrete products. Ash is an excellent substitute for cement. It contains calcium oxide, which has good cementitious characteristics. There is a reduction in cement consumption and improvement of the operational life of the building material. At the same time, the strength of the resulting mixture does not decrease, but on the contrary – increases (**Guanlei et.al., 2022**). Fly ash in dry form has no binding properties. It is activated after it interacts with the cement binder component. Thus, the cement consumption during the preparation of the concrete mix for polystyrene concrete is reduced to a large extent.

Thus, recycled fly ash can be utilized as a potential construction material to solve the problems related to utilization and also to save a considerable amount of cement consumed for concrete preparation (**Li et.al., 2022**). The use of industrial waste in construction has been achieved in many countries around the world, demonstrating the potential of this approach to improve the sustainability of the construction industry.

When analyzing the literature sources, the results of experimental tests of the technological characteristics of polystyrene concrete based on fly ash and water from the hydrosol removal channels were not found by the author. Therefore, it is necessary to conduct a study on the development of polystyrene concrete samples based on fly ash and water from hydrosol removal.

3 MATERIALS AND METHODS

In the research, the composition consisting of Portland cement (18-20 %), expanded polystyrene (5 % of the mass of cement dough), plasticizer (0,05-0,2 %), sand (44-48 %), water is taken as the control sample (11-15 %). For the investigated samples, the basic composition is as for the control sample, while replacing a part of the cement with 3-5-8-10-15 % fly ash, and also water from the hydraulic ash trap was added instead of ordinary water.

Raw material composition for polystyrene concrete contains portland cement (M450), granulated expanded polystyrene foam (strength 0,20-0,75 MPa, fractions 0-10 mm, bulk density - 20-30 kg/m^3), the form of mineral additive used was the fly ash from the ash dump of Petropavlovsk TPP, water was used from the hydro-ash removal facility TPP "Aluminum of Kazakhstan", additionally the bulk composition contains polyfractional sand and plasticizer.

In the manufacture of polystyrene concrete mixture, the Portland cement M450 Performa Plus 450 Jambyl Cement was used, the properties of which comply with **GOST 31108-2020 (Ordinary cements. Technical conditions)**.

The use of polystyrene foam as a filler is characterized by weight reduction and improvement of thermal insulation properties of the composite material.

Fly ash from ash dump of Petropavlovsk TPP is used in order to reduce the required consumption of Portland cement and the value of thermal conductivity coefficient of the polystyrene concrete produced.

Polyfractional sand acts as a stress distributor in the mass of adhesive cement binder so that the cement mixture does not crack when drying.

Plasticizer is used to increase the ease-of-use of the mixture, reduce the operational humidity and coefficient of polystyrene concrete. The Extraplast PC plasticizer was used in the work, which meets the requirements of **GOST 24211-2008**.

To obtain the raw material composition, molding of products is carried out from a moistened mixture of Portland cement, fly ash, polyfractional sand, polystyrene foam and water from the hydraulic ash removal facility.

Preliminary mechanical activation of fly ash is carried out, where it is intensively mechanically processed in mills-activators.

For dissolution, clean water is used, which meets the requirements of **GOST 23732-2011 (Mixing water for concrete and mortars)**. This means it must be potable or technical water, free from harmful impurities (acids, oils, excessive salts). The resulting solution is added to the dry mix and mixed for 1 minute at 150 rpm and then 2 minutes at 300 rpm. The dosed raw materials are mixed at 100 rpm.

Samples are poured into prismatic molds with the dimensions of 160 mm×40 mm×40 mm. Then the samples are shaken on a vibrating table to reduce air bubble formation and ensure proper compaction. The plastic concrete mixture is compacted for 30 s. After 24 hours, the samples are extracted and placed in a curing chamber at a temperature of 20 °C and a relative humidity of 95 %.

Standardized methods of cement dough testing were used in the study: determination of standard consistency, setting time of cement dough, determination of physical and mechanical parameters of concrete samples in accordance with regulatory documents. The samples were molded in accordance with **GOST 30744-2001 (Cements. Test methods using polyfractional standard sand)**. Samples of cement composition were prepared, portland cement was used as a binding material, corresponding to the requirements of **GOST 31108-2020**, sand was used as a fine and coarse aggregate, corresponding to the requirements of **GOST 8736-2014 (Sand for construction works. Technical characteristics)**. Determination of standard consistency and setting time of cements was carried out on a Vic's device in accordance with **GOST 310.3-1976 (Cements. Methods of determination of standard consistency, setting time and strength)**. Determination of flexural and compressive strength was carried out on a hydraulic press PGM-100 MG4A. Samples were made of a cement and tested in accordance with **GOST 310.4-1976 (Cements. Methods of determination of flexural and compressive strength)**.

The elemental composition was analyzed on X-ray fluorescence spectrometer PANalytical (Axios Max model (Rh 2.4 kW)). The phase composition was determined by X-ray diffraction on a smartLAB X-ray diffractometer manufactured by RigakuCorporation. The source of X-ray radiation is a CuKa (1.54059) X-ray tube. Распределение частиц по размерам образцов – зол, отобранных в золоотвалах, изучали с помощью лазерного анализатора (FRITSCH Analysette 22 Nanotec). The microstructures of raw materials were studied using a Tescan Vega 3 SBH scanning electron microscope with an AztecLive Lite Xplore 30 energy dispersive microanalysis system.

4 RESULTS AND DISCUSSION

When studying the properties of raw materials, an elemental analysis of the composition was carried out, as well as their analysis of the granulometric composition, SEM and RFA analysis of the structure of ash and slag waste.

For a purposeful utilization of fly ash and HARS as raw materials, and for a safe storage and utilization of ash and slag wastes, it is necessary to have information about their properties and characteristics. The average value from 5 samples is given.

The results of analyzing the composition of samples are shown in **Table 1**.

Table 1
Composition of fly ash and HARS

№	Element	Sample No. 1 (fly ash)	Sample No.2 (HARS)
1	A1	18,211	6,608
2	Si	39,724	18,327
3	P	0,71	1,717
4	S	0,21	
5	Cl	0,119	1,172
6	K	1,589	3,207
7	Ca	9,896	13,350
8	Ti	2,996	
9	V	0,062	
10	Ml	0,502	
11	Fe	23,968	2,852
12	Ni	0,001	
13	Zn	0,018	
14	Ga	0,013	
15	As	0,004	
16	Rb	0,012	
17	Sr	0,189	
18	У	0,025	
19	Zr	0,040	
20	Nb	0,006	
21	Sr	0,032	0,025
22	Te	0,022	0,017
23	Ba	0,326	
24	Eu	0,132	
25	Yb	0,015	
28	Ir	0,000	
29	Pb	0,004	

As it can be observed from Table 1, compounds of the main ash-forming macroelements such as Si, Al, Fe, O, Ca, Ti, Mg, S, K, Na make up 98-99 % of ash and slag waste. Other trace elements are contained in ash in concentration of 0,1 % and less. During the coal combustion some of the trace elements such as Sr, Ba, Sc, Y, La, Ti, Zr, etc. are concentrated in the slag. Other elements (Ga, In, Tl, Ge, Sn, Pb, etc.) at temperatures above 1000 ˚C volatilize from the high temperature zone and settle in electrostatic precipitators (at 110-120 ˚C).

Increasing the degree of crushing of fly ash has a positive effect on the strength and durability of concrete containing fly ash. To achieve the required specific surface area, the fly ash was additionally crushed in a planetary mill (PM 100). The grinding process was carried out for (30 minutes) until a specific surface area of (400 m^2/kg) was reached. Replacing cement with the original ash reduces the pore size of the cement paste, and the addition of crushed ash leads to a further reduction in the pore size of the cement stone. Particle size distribution can be represented in the form of a histogram - dependence of the number of particles on the particle size. **Figure 1** shows graphs of particle size distribution of samples - ashes taken from ash dumps.

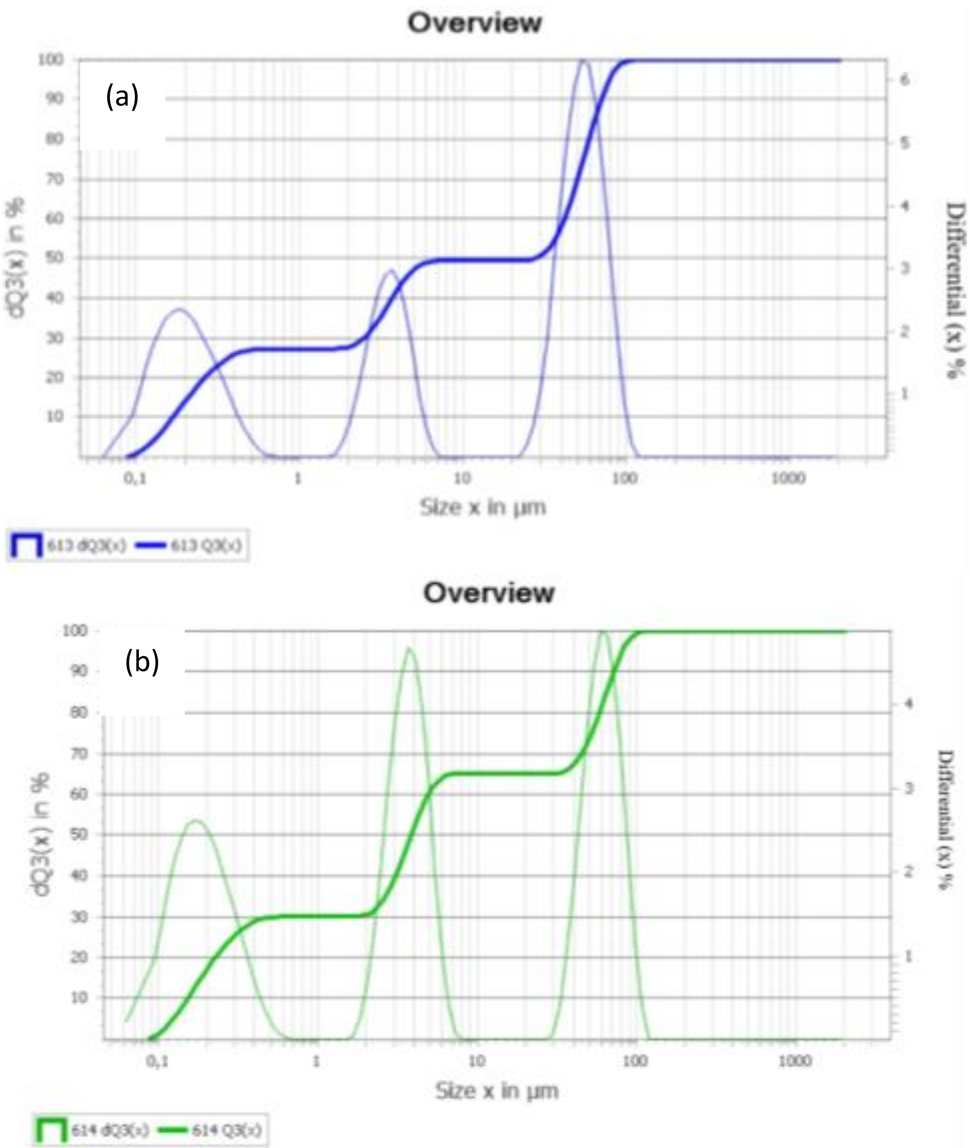

Figure 1 - Particle size distribution: (a) fly ash sample; (b) water from hydro-ash removal systems (HARS) (author’s material)

As can be seen in Figure 1(a), 70-90 % of fly ash is in sizes from 50-70 microns, 10-40 % - from 0,2 to 3,9 microns. For ash containing water (Fig. 1(b), 70-90 % of fly ash is in sizes from 23-36 microns, 10-40 % - from 0,2 to 0,3 microns.

Laser particle size analysis shows that the particle size and distribution of fly ash are normal, and the distribution range is wide. This shows that the total particle size of the fly ash is uniform, but the distribution is relatively dispersed.

Fly ash particles are compact spheres and aggregates with particle sizes from 10 to 100 microns. From the above data, it can be concluded that this sample is very finely dispersed. Fly ash contains silicon dioxide (SiO), calcium oxide (CaO), aluminum oxide (AlO) and iron oxide (FeO). **Figure 2** shows microphotographs of a fragment of fly ash particle, where it can be seen that the particles consist of glass phase with liquation products, metal compounds.

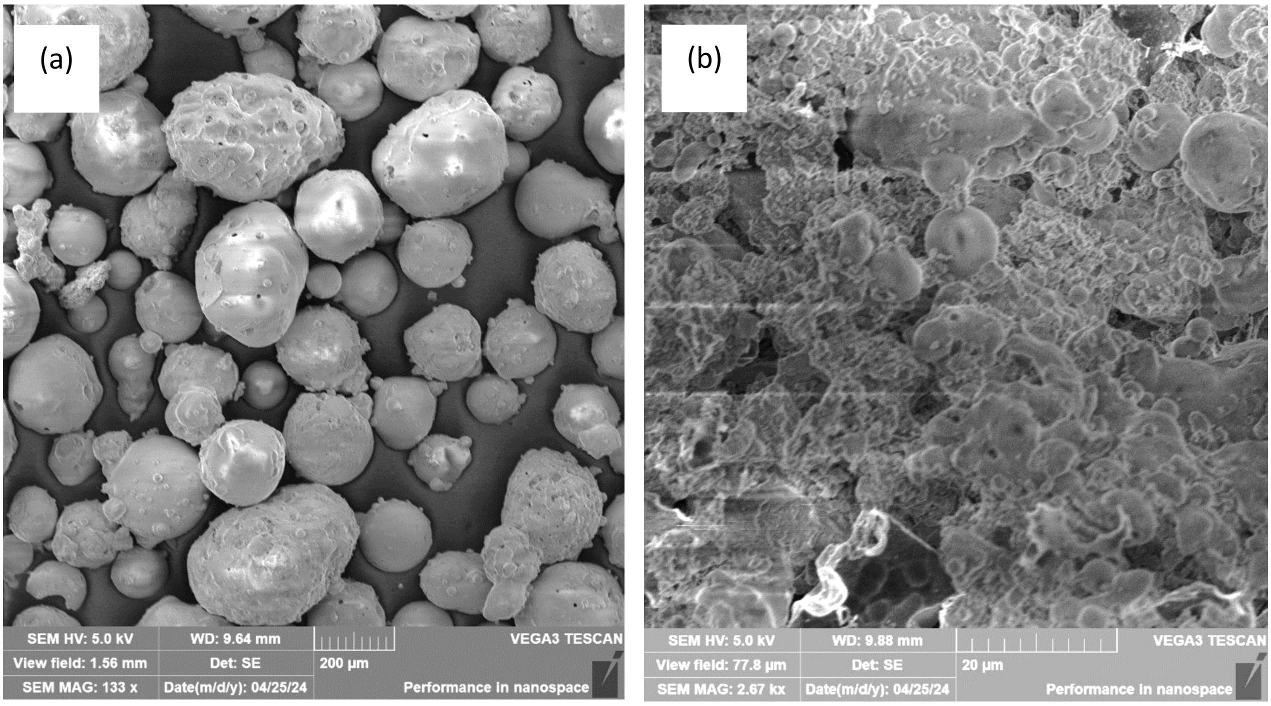

Figure 2 - Microphotographs of fly ash samples: (a) fly ash; (b) HARS (author's material)

As shown in Figure 2, fly ash is formed as a result of rapid cooling of molten ash. Consequently, most of the fly ash particles are in an amorphous state. Fly ash particles are typically spherical in shape and have a diameter of less than 1 to 150 microns, while the size of cement particles is less than 45 microns. This spherical shape and particle size increase the fluidity of the concrete mix and reduce the need for water. Studies have shown that fly ash is evenly distributed, has a regular spherical shape, smooth surface and fine particles. During the observation process, it was also discovered that there were some irregularly shaped particles that could form after a decrease in temperature.

The features of composites' structure formation processes containing industrial waste dispersions were revealed by means of structural analysis by X-ray method. **Figure 3** shows the phase composition of microspheres.

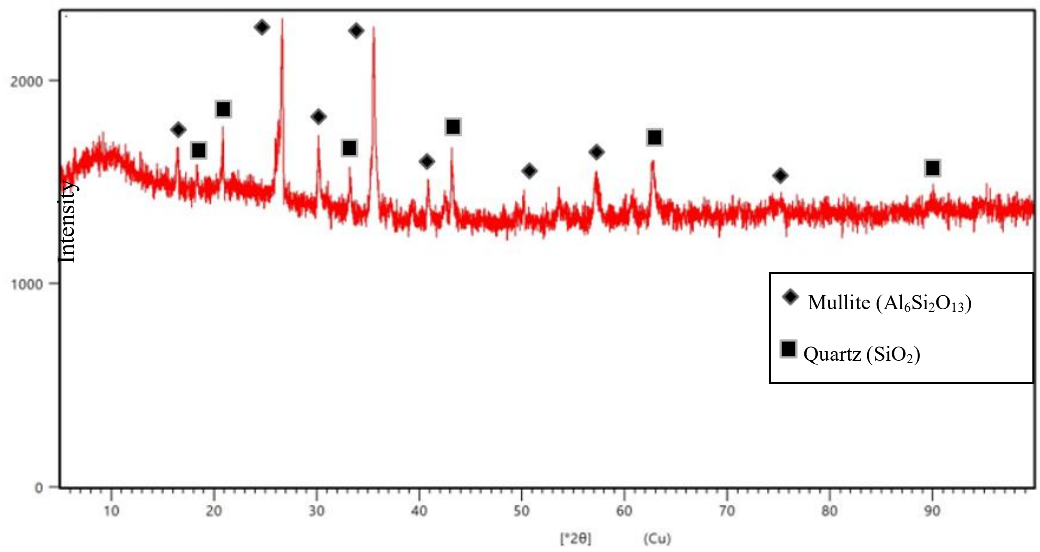

Figure 3 - X-ray phase analysis of microspheres (author's material)

According to the data of structural analysis by X-ray method, microspheres are represented by a mixture of mullite and quartz phases. The phase composition of microspheres determines their morphology, samples with a high content of X-ray amorphous phase are formed in the form of thin-walled microspheres, samples containing mullite phase are characterized by relief and perforated shell morphology.

During the study of the technological properties of the polystyrene concrete mixture, the physical and mechanical characteristics were determined: standard consistency, setting time, compressive strength.

The results of the study are summarized in **Table 2**.

Table 2
Results of a study to determine the standard consistency of cement dough

№	Sample	Standard consistency, %
1	Control sample, Portland cement M450	28,75
2	cement+3 % fly ash	28,7
3	cement+5 % fly ash	26,25
4	cement+8 % fly ash	25,5
5	cement+10 % fly ash	25,25
6	cement+15 % fly ash	24,5

Table 2 shows that increasing the amount of fly ash to 20 % reduces the amount of water for mixing cement batter by 4 %. Fly ash has an effect on the standard consistency of cement batter, which will have an effect on reducing shrinkage due to the water-soluble effect of fly ash and reducing the risk of thermal cracking due to reduced heat release.

It is important to establish the effect of additives on setting time of cement. The results of the study of the effect of additives on the setting time of cement are shown in **Table 3**.

Table 3

Results of research on the effect of additives on the setting time of cement

№	Sample	Beginning of setting (hour, minutes)	End of setting (hour, minutes)
1	Control sample, Portland cement M450	3 h. 30 min.	4 h.30 min.
2	cement+3 % fly ash	3 h. 00 min.	4 h. 30 min.
3	cement+5 % fly ash	2 h. 50 min.	4 h. 40 min.
4	cement+8 % fly ash	3 h. 20 min.	4 h. 30 min.
5	cement+10 % fly ash	3 h. 25 min.	4 h. 55 min.
6	cement+15 % fly ash	3 h. 30 min.	4 h. 40 min.
7	cement+20 % fly ash	3 h. 00 min.	4 h. 30 min.

Table 3 shows that addition of fly ash from ash dump of Petropavlovsk TPP affected the setting time of cement dough. The beginning of setting of cement dough with addition of 10 % of ash in comparison with cement without additives is reduced by 5 min, and with addition of 20 % - by 30 minutes.

Studies on determination of standard consistency and setting time of cement dough showed that the best readings are No. 6 and No. 7, with "fly ash" additions of 15 % and 20 %, respectively.

The initial setting time with the addition of 20 % fly ash was reduced by 30 minutes. Especially this indicator is important for winter concreting in the northern regions of our country.

On increasing the dosage of ash as aggregate, the compressive strength increased as compared to the control specimen as shown in **Table 4**. In this case, the samples were prepared with the addition of plain water. The samples contained plasticizer from 0.05-0.2 % depending on the weight of cement.

Table 4

Compressive strength test results

No.	Sample	Fly ash, %	Curing time, days	Compressive strength, MPa
1	Control sample (M450)	0	3	7,3
2		0	7	9,6
3		0	28	11,7
4	With fly ash	10	3	8,5
5		15	3	10,2
6		10	7	15,1
7		15	7	12,2
8		10	28	16,8
9		15	28	17,4

Table 5 shows the results of compressive strength tests of samples with the addition of water from hydraulic traps. The tested samples contained from 10 to 15 % fly ash. The samples also contained a plasticizer from 0,05-0,2 %, depending on the weight of the cement.

Table 5

The results of compressive strength tests of samples based on HARS

No.	Sample	Fly ash, %	Curing time, days	Compressive strength, MPa
1			3	9,5
2		10	3	8,5
3		15	3	10,0
4			7	11,2
5		10	7	10,1
6		15	7	13,2
7			28	16,3
8		10	28	21,8
9		15	28	23,3

Analysis of the results of physical and mechanical tests showed that in the first 3-7 days of curing, the introduction of fly ash in an amount of up to 8 % caused a decrease in the cement strength of concrete. After 28 days, the fly ash added specimens had a strength 7 % higher than the control specimens. The slow growth in strength of cements with fly ash is due to slower hydration processes. The final stable structure in such cements is reached later than in conventional cement mixtures.

The results obtained showed that all the strength values for the concrete with polystyrene containing fly ash were higher than the control concrete sample. The highest value was obtained for the concrete containing 5 % polystyrene and 10 % fly ash as the increase in strength was 12 %. The lowest value was associated with the control specimen which did not contain ash.

As shown by the elemental composition analysis data, the used ash contains silica and aluminum. The aluminosilicate particles act as pozzolans in cement stone and the initial setting time of cement pastes was slightly different from the setting time of pastes without additives. The hardening processes are related to the corrosion of the surface of ash particles by calcium hydroxide $Ca(OH)_2$ released during the hydration of cement.

To obtain information about the phase composition of the cement sample with 10 % fly ash (**Fig. 5**) and the control mix without fly ash addition (**Fig. 4**), XRD analysis was carried out. For XRD analysis, concrete samples were taken after passing the compressive strength test. The coarse aggregate particles were removed from the samples and the remaining hardened cement-sand mortar was subjected to grinding in an agate mortar. No. 008 sieve was used for the sampling. The resulting powder was then placed in a uniform layer in the cuvette and flattened at the edges. The decrease in the amount of free Ca^{2+} is due to its transfer to calcium hydrosilicates during interaction with water from hydraulic ash removal. According to the results of X-ray phase analysis it can be seen that the sample of cement stone with replacement of part of cement with ash from hydraulic ash removal (**Fig.5**) is characterized by a reduced content of calcium hydroxide.

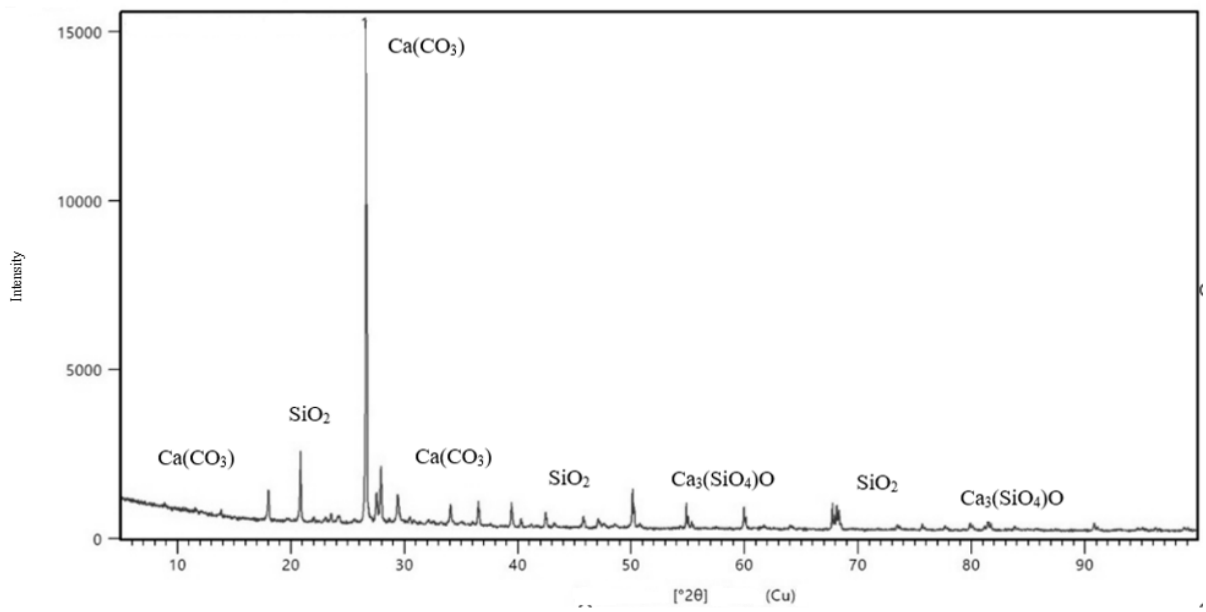

Figure 4 - Composition No. 1 (Control sample) (author's material)

During the early curing periods, water-thick interlayers filled with $Ca(OH)_2$ crystals were observed between cement particles and fly ash, which is also in agreement with other studies (**Szostak & Golewski, 2020**). Subsequently, due to the interaction between $Ca(OH)_2$ and the ash phase, the formation of calcium hydrosilicates and other new formations began, compacting and hardening the cement stone. The obtained X-ray radiographs of the samples indicate an increased amount of calcium hydrosilicates in the composition with fly ash (composition № 2), compared to the control composition. Also, according to X-ray radiograms it can be observed that the composition with fly ash decreased the amount of calcium carbonate, which confirms the binding of calcium hydroxide by silica and the formation of stronger compounds.

X-ray phase analysis of the composition with replacement of 10 % of cement with fly ash and the control sample confirmed the pozzolanic reaction in the ash compositions.

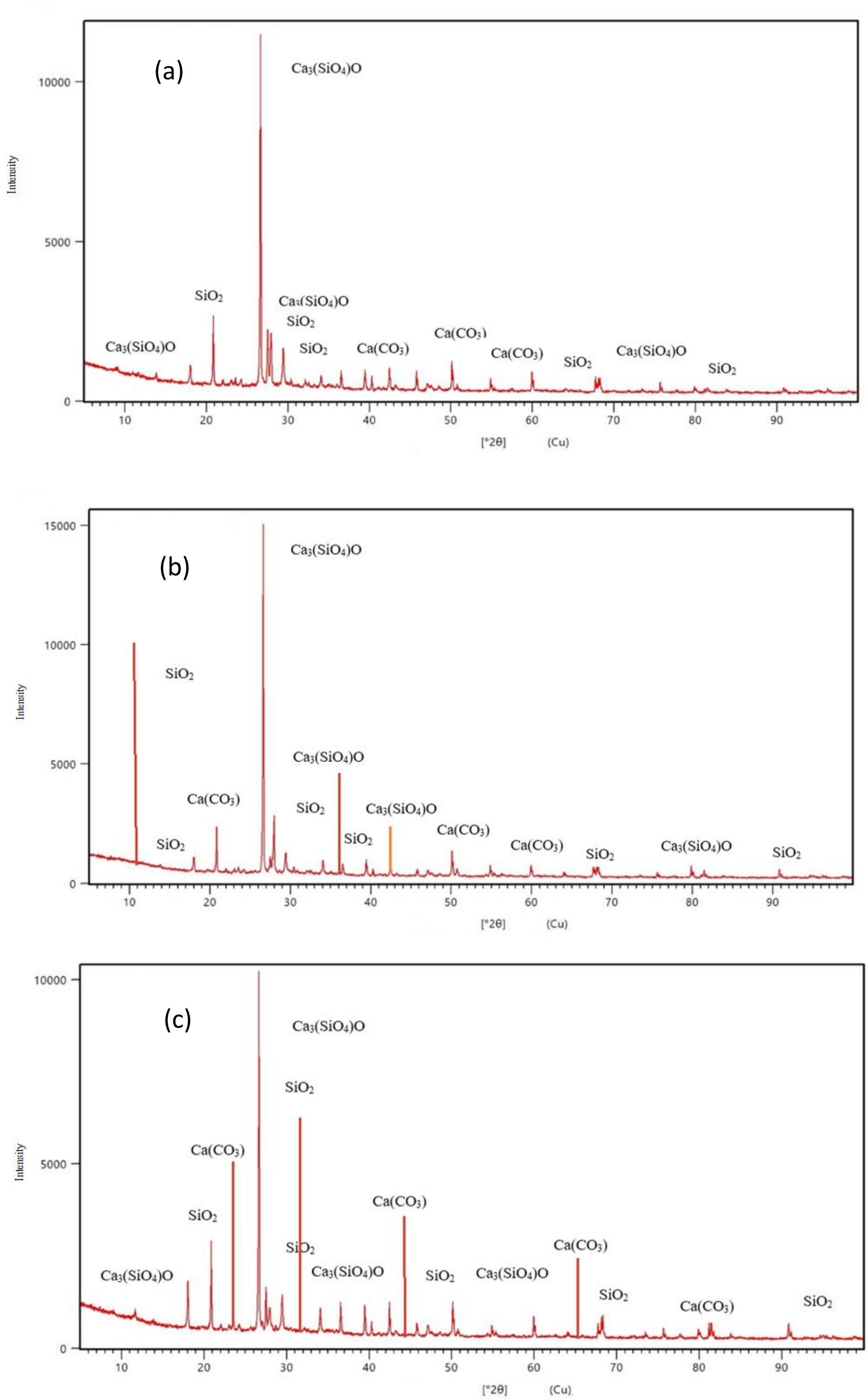

Figure 5 - Composition No. 2 with 10 % Fly Ash and HARS: (a) 3 days; (b) 7 days; (c) 28 days curing (author's material)

Ash in concrete contributes to the formation of a dense structure of the intergranular space of aggregates and a less defective contact zone of aggregates with cement stone (**Makhmudov et.al., 2021**). This is due to the higher degree of hydration of cement and reactions between calcium hydroxide and ash components to form an additional amount of calcium hydrosilicate gel with a cryptocrystalline structure (**Tolegenova et.al., 2023**). Currently, based on experimental data on the selection of rational compositions and the study of the technological characteristics of polystyrene concrete obtained in this research work, new compositions of polystyrene concrete with an increased strength index have been developed.

5 CONCLUSIONS

Based on the results of the conducted research, the following conclusions can be drawn:

1. As a result of studies of the chemical composition of raw materials, namely fly ash and ash containing water, it was found that the average concentrations of Ba (barium), Sr (strontium) and Zr (zirconium) in the initial samples are less than 1 %, which is safe for use in the production of concrete. When studying the granulometric composition, the ash particles had sizes from 10 to 100 microns. This means that the smaller the size of the ash particles, the higher its activity and hydration rate. The spherical shape and particle size increase the fluidity of the concrete mix and reduce the need for water, which was confirmed when determining the standard consistency, which decreased to 24,5 %.

2. Also, in the study of the technological properties of polystyrene concrete samples with the above-mentioned additives have shown the evidence of an increase in strength values after 28 days of curing.

3. Calcium hydrosilicates are formed in cement stone samples with hydrous ash, which increase the strength, reduce porosity and water absorption of products made of them.

4. Specifically, the composition developed in this study enabled a cement economy of 20% (by replacing cement with fly ash) and ensured 100% replacement of clean tap water with highly mineralized HARS effluent, thus directly minimizing the use of primary natural resources and enhancing the sustainability of the construction industry.

5. Experimental studies conducted during the work prove that additives affect the strength of polystyrene concrete, as well as many other types of lightweight concretes. At the same time, the properties of additives and its content in the mortar matrix also affect the strength of the cement matrix.

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