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RESEARCH ARTICLE

HYPERPRESSED BRICKS USING FLY ASH FROM THERMAL POWER PLANTS

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Abstract. *The article is devoted to the study of the potential of using ash from thermal power plants (TPP) as a partial replacement for the main raw material in the manufacture of hyper-pressed bricks. The relevance of the work is due to the need to develop environmentally and economically feasible approaches to the disposal of large-scale industrial waste, such as waste ash from thermal power plants, while simultaneously creating building materials with improved characteristics. In the course of the study, a number of samples of hyper–pressed bricks with different concentrations of TPP ash were produced and analyzed - up to 40% by weight of binder. To evaluate the effectiveness of the replacement and determine the optimal composition, tests were carried out to determine the physical and mechanical properties of the obtained products, in particular, compressive strength. It has been found that the optimal composition of hyper-pressed bricks with the addition of TPP ash makes it possible to obtain products with a strength grade (≥M150) comparable to the requirements for traditional building bricks. The most effective use of ash as a filler is achieved when its concentration is up to 40% by weight of the binder component. IR spectrometry and SEM analysis methods have been successfully applied to confirm chemical and structural changes in the material. The results of IR spectrometry clearly showed a decrease in the intensity of the peak of calcium hydroxide ($Ca(OH)_2$) and the shift of the silicate gel peak (C-S-H) over time.*

Keywords: *hyper-pressed brick, thermal power plant ash, IR spectrometry, pozzolan reaction, C-S-H gel, durability, waste disposal, environmental friendliness.*

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ҒЫЛЫМИ МАҚАЛА

ЖЫЛУ ЭЛЕКТР СТАНЦИЯЛАРЫНЫҢ КҮЛІ ҚОЛДАНЫЛҒАН ГИПЕРПРЕССТЕЛГЕН КІРПІШ

Ж.Т. Ибраева[1], **А.А. Ибжанова**[1], **Р.К. Ниязбекова**[1], **С.С. Алдабергенова**[1], **Я. Циеслик**[2]

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Аңдатпа. *Мақала гиперпресстелген кірпіш өндірісінде негізгі шикізатты ішінара ауыстыру ретінде жылу электр орталықтарының (ЖЭО) күлін қолдану әлеуетін зерттеуге арналған. Жұмыстың өзектілігі жақсартылған сипаттамалардан тұратын құрылыс материалдарын алу арқылы ЖЭО күлі сияқты ірі тоннажды өнеркәсіптік қалдықтарды кәдеге жаратудың экологиялық және экономикалық тұрғыдан тиімді тәсілдерін әзірлеу қажеттілігімен байланысты. Зерттеу барысында ЖЭО күлінің яғнитұтқыр заттың массасы бойынша 40% дейін әртүрлі концентрациясынан тұратын гиперпресстелген кірпіштің бірқатар үлгілері жасалды және талданды. Алмастыру тиімділігін бағалау және оңтайлы құрамды анықтау үшін алынған өнімдердің физикалық-механикалық қасиеттерін, атап айтқанда қысу беріктігін анықтау бойынша сынақтар жүргізілді. ЖЭО күлі қосылған гиперпресстелген кірпіштің оңтайлы құрамы дәстүрлі құрылыс кірпішіне қойылатын талаптармен салыстырылатын беріктігі (≥М150) маркалы бұйымдарды алуға мүмкіндік беретіні анықталды. Толтырғыш ретінде 40%-ға дейінгі концентрациясында күлді барынша тиімді пайдалануға оның тұтқыр компоненттің массасы бойынша қол жеткізіледі. Материалдың химиялық және құрылымдық өзгерістерін растау үшін ИҚ спектрометриясы мен СЭМ талдау әдістері тиімді қолданылды. ИҚ спектрометриясының нәтижелері кальций гидроксиді шыңының ($Ca(OH)_2$) қарқындылығының төмендеуін және уақыт өте келе силикат гелінің (C-S-H) шыңының түзілуін көрсетті.*

Түйін сөздер: *гиперпресстелген кірпіш, ЖЭО күлі, ИҚ спектрометриясы, пуццолан реакциясы, C-S-H гелі, беріктігі, қалдықтарды кәдеге жарату, экологиялық таза.*

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НАУЧНАЯ СТАТЬЯ

ГИПЕРПРЕССОВАННЫЙ КИРПИЧ С ИСПОЛЬЗОВАНИЕМ ЗОЛЫ ТЕПЛОЭЛЕКТРО СТАНЦИЙ

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Аннотация. *Статья посвящена исследованию потенциала применения золы теплоэлектроцентралей (ТЭЦ) в качестве частичной замены основного сырьевого материала при изготовлении гиперпрессованного кирпича. Актуальность работы обусловлена необходимостью разработки экологически и экономически целесообразных подходов к утилизации крупнотоннажных промышленных отходов, таких как зола уноса ТЭЦ, с одновременным созданием строительных материалов с улучшенными характеристиками. В ходе исследования был изготовлен и проанализирован ряд образцов гиперпрессованного кирпича с различной концентрацией золы ТЭЦ – до 40% по массе вяжущего. Для оценки эффективности замены и определения оптимального состава были проведены испытания по определению физико-механических свойств полученных изделий, в частности, прочности на сжатие. Установлено, что оптимальный состав гиперпрессованного кирпича с добавлением золы ТЭЦ позволяет получить изделия с маркой по прочности (≥М150), сопоставимой с требованиями к традиционному строительному кирпичу. Максимально эффективное использование золы в качестве наполнителя достигается при ее концентрации до 40% по массе вяжущего компонента. Методы ИК-спектрометрии и СЭМ-анализа были успешно применены для подтверждения химических и структурных изменений в материале. Результаты ИК-спектрометрии однозначно показали снижение интенсивности пика гидроксида кальция ($Ca(OH)_2$) и смещение пика силикатного геля (C-S-H) со временем.*

Ключевые слова: *гиперпрессованный кирпич, зола ТЭЦ, ИК-спектрометрия, пуццолановая реакция, C-S-H гель, прочность, утилизация отходов, экологичность.*

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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

The study of the production of hyper-pressed bricks with partial replacement of raw materials with ash from thermal power plants in Kazakhstan has scientific and practical significance aimed at resource conservation and improving the environmental situation in the country. The modern construction industry faces a double challenge: the need to reduce CO2 emissions in the production of traditional binders (primarily Portland cement). One of the most significant wastes in terms of volume is ash and slag waste generated as a result of coal combustion at thermal power plants (TPPs). The annual volume of solid waste generation is estimated at millions of tons, and their storage occupies vast territories and creates environmental risks. Kazakhstan, being a major producer of coal-based electricity, is facing an acute problem of accumulation of ash and slag waste (ASW) generated as a result of the operation of thermal power plants (TPPs) and state district power plants (SDPPs). The low level of utilization (only 3-8%) indicates that 92-97% of the waste generated annually ends up in ash dumps.

A promising direction for the disposal of such technogenic materials is their use in the production of building products as an active or inert filler. The hyper compression method (semi-dry pressing under high pressure followed by curing) is optimally suited for working with ASF. Unlike traditional kiln-fired bricks, hyper-pressed products do not require high-temperature processing, which significantly reduces energy consumption and the cost of finished products. Fly ash, having a fine dispersion and amorphous phase, can act as a pozzolan additive by interacting with calcium hydroxide ($Ca(OH)_2$) cement binder with the formation of an additional durable silicate gel (C-S-H).

However, despite the obvious advantages, the widespread adoption of hyper-pressed bricks with a high ash content is hindered by a lack of understanding of the kinetics of curing and the long-term stability of the microstructure, especially when using non-activated ash. Detailed scientific evidence is required that the pozzolan activity of ash under super pression conditions guarantees the required strength properties and durability.

The objective of the present work is to scientifically substantiate the strength and structural characteristics of hyper-pressed building bricks using thermal power plant ash.

In order to achieve the objective, the following main tasks were formulated:

1.To determine the optimum content of TPP ash in the hyper pressed mixture, providing maximum strength gain.

2.To carry out a comprehensive assessment of physical and mechanical properties (compressive strength) of the obtained samples.

3.Analyze the microstructure of the samples using scanning electron microscopy (SEM) to evaluate the distribution of ash particles and the nature of their interaction with the cement matrix.

4.Using infrared spectrometry to analyze the phase composition of cement stone at different curing times to quantitatively confirm the course of the pozzolanic reaction and the formation of secondary binding products (C-S-H gel).

Scientific novelty of the work consists in the establishment of quantitative correlation between ash content, dynamics of phase composition change (confirmed by IR spectrometry) and development of strength of hyper-pressed products, which allows to scientifically substantiate the mechanisms of their hardening.

The practical value of the work lies in the development of specific recommendations on the composition and technology of production of high-strength hyper-pressed bricks with a high degree of cement replacement for ash, which opens the way to the creation of an environmentally friendly and economically profitable building material.

2 LITERATURE REVIEW

Numerous works by domestic and foreign scientists have been devoted to the study of the properties of fly ash and its interaction with various binders and mineral components. Special attention in these studies is paid to the effect of fly ash on the strength characteristics, water absorption, frost resistance and durability of building materials. The analysis of scientific sources makes it possible to systematize data on the methods of ash activation, the conditions of its use, as well as on the compositions of mixtures containing this component.

Scientists have found that adding ash, especially in small amounts (up to 20%), increases the strength of concrete. The main purpose of the study was to determine the possibilities and limitations of using TPP ash as a mineral additive in concrete, as well as to evaluate its effect on physical and mechanical properties, primarily on strength characteristics (**Ferraro et al., 2021**).

The addition of activated ash in doses of 5-10% can significantly improve the frost resistance of these materials. The aim of the study was to determine the effect of addition of activated ash from thermal power station on the frost resistance of concrete and brick products, and to identify the mechanisms underlying this improvement. In the course of the work the dependence between the amount of ash in the mixture and its influence on the resistance of materials to cyclic freezing and thawing was established (**Lachheb et al., 2023**).

Thermal activation of ash from TPPs (calcination at 600-800°C) significantly increases its pozzolanic activity, which makes it a more effective additive in hyper-pressed bricks and cement mortars. The calcination of ash at 700°C significantly increases its activity by eliminating carbon, resulting in the formation of stronger bonds in cement stone. Mechanical activation (grinding of ash) reduces its particles to microscopic size, which also helps in increasing the activity. However, the high cost of calcination and the need to optimize the temperature and time of activation remain problems (**He et al., 2023**).

The utilization of TPPs ash as an additive in building materials was analyzed. The author came to the conclusion that the use of ash reduces the load on ash dumps and allows efficient waste processing, which reduces the negative impact on the environment. Besides, the economic benefit was noted, as the use of ash instead of cement significantly reduces the cost of production of construction materials (**Ghouleh et al., 2023**).

The work of emphasized on the fact that the use of ash in building materials contributes to the reduction of CO_2 emissions, as a large amount of carbon dioxide is emitted during cement production. The use of ash reduces the cement demand, which is directly related to the reduction of carbon footprint (**Salamanova et al., 2021**).

The economic and environmental efficiency of hyper compression technology, which allows the use of large volumes of industrial waste (such as ash and slag from thermal power plants, waste from mining or metallurgical industries) as the main raw material component for the production of building material were discussed in detail (**Li et al., 2022**).

Environmental assessment has shown that the use of fly ash from TPPs as a secondary raw material for the production of construction materials is one of the most effective ways to reduce the burden on the environment, as it simultaneously reduces the volume of industrial waste storage and reduces the need for extraction and processing of natural resources (**Samantasinghar & Singh, 2020**).

Studies have shown that the introduction of thermal power plant ash into the composition of hyper-pressed bricks contributes not only to the utilization of large-scale industrial waste, but also provides a significant increase in strength and a decrease in water absorption of the final building material, which proves the high efficiency of using ash in the technology of production of fats-free binders (**Bo et al., 2021**).

The urgency of introducing secondary resources, such as TPP ash, into the technological cycles of construction production is due not only to the environmental need to reduce waste disposal, but also to the potential for creating composites with improved properties, subject to strict requirements. technological modes (**Guanlei et al., 2022**).

The introduction of innovative approaches to recycling waste from combined TPPs allows not only to solve acute environmental problems, but also to create a new generation of efficient and resource-saving building materials, thus integrating the concept of circular economy into the construction industry (**Maria Harja et al., 2022**).

The use of ash from thermal power plants as a secondary raw material in the production of building materials (e.g., bricks) leads to significant savings of natural resources and reduction in the cost of final products. This approach allows enterprises not only to reduce the cost of raw materials, but also to solve the problem of utilization of large volumes of industrial waste (**Mukhtar et al., 2022**).

The use of TPP as a mineral additive in construction mixtures allows not only to reduce the need for expensive Portland cement, but also comprehensively improve the technological and operational characteristics of final materials, including density and durability (**Cretescu et al., 2021**).

Some authors have investigated the effect of activated fly ash on the characteristics of hyper-pressed bricks. They found that using these industrial wastes not only makes it possible to efficiently dispose of ash, but also significantly increases the strength and durability of hyper-pressed bricks (**Ana María Ospina Salazar et al., 2023**). Thus, activated ash acts as an effective technogenic component that improves the quality of building material (**Khamit et al., 2024**).

The use of thermal power plant fly ash as an active mineral component of construction mixtures allows not only to reduce the material intensity and cost of the final product by replacing part of the cement, but also to achieve an improvement in technological and strength characteristics **(Pashkov and Bogdanov 2016**). In particular, introduction of ash contributes to the increase of density, frost resistance and resistance of cement systems to aggressive media (**Syndarbekova et al., 2025**).

3 MATERIALS AND METHODS

The following components were used to manufacture samples of hyper-pressed bricks:

Cement of M-450 grade according to **GOST 31108 (Cements for general construction. Technical conditions)** was used. Portland cement was used as the main binding agent. Tap water complying with the requirements of **GOST 23732 (Water for concrete and mortars)** was used. Fly ash (fly ash) of class F (high silica) according to **GOST 25818 (Fly ash from thermal power plants for concrete. Technical conditions)** was used. The ash was used without additional activation with minimal drying. Chemical composition (by XRF method, using the spectrometer ARL QUANT'X (Thermo Scientific, USA) and dispersibility (specific surface area by Blaine) were determined. Quartz sand was used as the main filler, which was partially replaced by ash. Optimization of composition and ratio. The percentage of cement replacement with ash (by weight of binder) was the main variable parameter and was 0% (control sample), 20%, 35 % and 40%. Water cement ratio: was kept constant (or optimum for hyper compression) in the range of 0.08-0.12.

The components (cement, fly ash, aggregate) were dosed to an accuracy of ±0.1% by weight.

Mixing was carried out in a laboratory forced-action mixer. Initially, the dry components were mixed for 3 minutes, then water was added and the process continued until a homogeneous semi-dry mixture with optimum moisture content for pressing was obtained.

Brick or bar shaped specimens of 4x4x16 cm (for laboratory tests) were produced using a hydraulic press (HTP-100, produced by Hydraulic Systems (Russia). Uniaxial pressure in the range of 20-30 MPa (typical for hyper-pressing) was applied. The specimens were molded from the calculated mass of the mix, providing a standard density.

After pressing, the specimens were removed from the molds. The specimens were cured under normal conditions (temperature 20±2°C, relative humidity ≥ 95%). Tests were carried out at durations: 7, 28 and 90 to evaluate the kinetics of strength gain.

Physical-mechanical tests: Compressive strength was determined according to **GOST 10180 (Concretes. Methods of determining strength by control specimens)** on cube specimens or half beams, using a hydraulic press.

Micro structural analysis: scanning electron microscopy (SEM) (JEOL JSM-6490LV) with energy dispersive analysis system (EDS/EDS). Small cement stone fragments (size ≤1 cm) at specified curing times. Infrared spectrometry (Fourier-transform infrared spectroscopy, Alpha II FTIR): Powdered cement stone samples at different curing times were mixed and pressed into tablets to identify the phase composition and quantify the pozzolanic reaction. The sharp peak of $Ca(OH)_2$ at 3640 cm^{-1} was monitored (decrease in its intensity indicates consumption). Analyzing the shift and intensity change of the C-S-H (valence vibrations of Si-O) peak in the 950-1000 cm^{-1} region (shift to and enhancement indicates secondary gel formation).

4 RESULTS AND DISCUSSION

When TPPs ash is used for the production of building materials, those impurities that can be harmful to human health or the environment, as well as those that can impair the durability of the building material itself, are considered hazardous.

The chemical composition of ash determined by X-ray fluorescence analysis (XRF) is critical for the evaluation of pozzolanic activity (**Table 1**).

Table 1
Chemical composition of ash [author's material]

№	Component	Content (% wt.)
1	SiO_2	46,3
2	Al_2O_3	28,5
3	Fe_2O_3	4,9
4	CaO	5,2

Such key components as SiO_2, Al_2O_3, Fe_2O_3, and their high content indicate a good pozzolan ability of ash. In turn, this ability allows it to enter into a chemical reaction with calcium hydroxide, which is formed during the hydration of cement (the main binder in hyper-pressed bricks). A high CaO content can give the ash independent astringent properties that affect the setting speed. However, excess can lead to instability (expansion) of the material. The content of calcium oxide in the ash is 5.2%, which will actively interact with $Ca(OH)_2$ cement to form a secondary C-S-H gel, which over time will lead to an additional increase in strength and compaction of the structure. No high sulfate content was found, which can cause sulfate corrosion and destruction of the cement stone in the long term. No impurities of As, Pb, Hg, Cd, Cr, Ni were found in the ash.

The specific surface of ash was determined by the air permeability method (according to Blaine) according to the corresponding standard **(GOST 310.2 Cements. Methods of determination of grinding fineness) (Table 2)**.

Table 2
Result of specific surface area determination [author's material]

Raw material	Determination method	Specific surface, $S_{(y)}$ (cm^2/g)
TPPs ash (investigated material)	Blaine	3673
Ordinary Portland cement (for comparison)	Blaine	3462

The results of physical and mechanical tests, name lycom pressive strength (curing kinetics) are summarized **in Table3**.

Table 3
Compressive strength (hardening kinetics) [author's material]

Composition (Ash Substitution)	Strength at 7 days (MPa)	Strength at 28 days (MPa)	Strength at 90 days (MPa)
Control (0% Ash)	19	25	34
Optimal Composition (20% Ash)	13	14,5	18,3
Optimal Composition (35%Ash)	15	17,6	26,3
Optimal Composition (40% Ash)	17	23,4	35,9

The ash samples show a decrease in strength at an early stage (7-28 days) compared with the control composition. This is due to the slower initial hydration of cement due to the dilution effect (reducing the proportion of cement in the total binder mixture) and the slower nature of the pozzolan ash reaction compared to the rapid hydration of Portland cement..

By 28 days, specimens with optimum ash content (up to 40% by weight of binder) show equalization or approximation of strength to that of the control mix. This effect becomes even more pronounced at 90 days and beyond.

This confirms that the slow pozzolanic reaction between the amorphous SiO_2 of the ash and the released $Ca(OH)_2$ successfully compensates for the initial strength deficiency. The formation of a secondary, denser C-S-H gel provides additional strength gains at later dates, which is a key factor for the durability of the hyper-pressed brick.

The resulting hyper pressed bricks are of grade ≥M150, confirming the suitability of the ash for the production of high-strength products.

The results of microstructural and phase analysis are shown in **Fig.1and 2 (a, b, c).**
IR spectrometry **(Fig. 1)** provided quantitative evidence of the pozzolanic reaction occurring, explaining the long-term strength increase.

In **Fig. 1 (a)** the observed position of the broad C-S-H peak (in the region of 900-1100 cm^{-1}) shifts towards lower frequencies (960 cm^{-1}) during prolonged curing. This shift is a key indicator that the C-S-H gel becomes more low-based due to reaction with SiO_2 ash, indicating the formation of a secondary, denser binder.

The low intensity of the $CaOH_2$ band (870 cm^{-1}) in the ash sample confirms that most of this hydroxide is consumed by the pozzolanic reaction rather than remaining free. The intensity of such a peak is a marker: its decrease compared to the control composition or earlier times is direct evidence of the consumption of Ca $(OH)_2$ by the ash during the pozzolanic reaction.

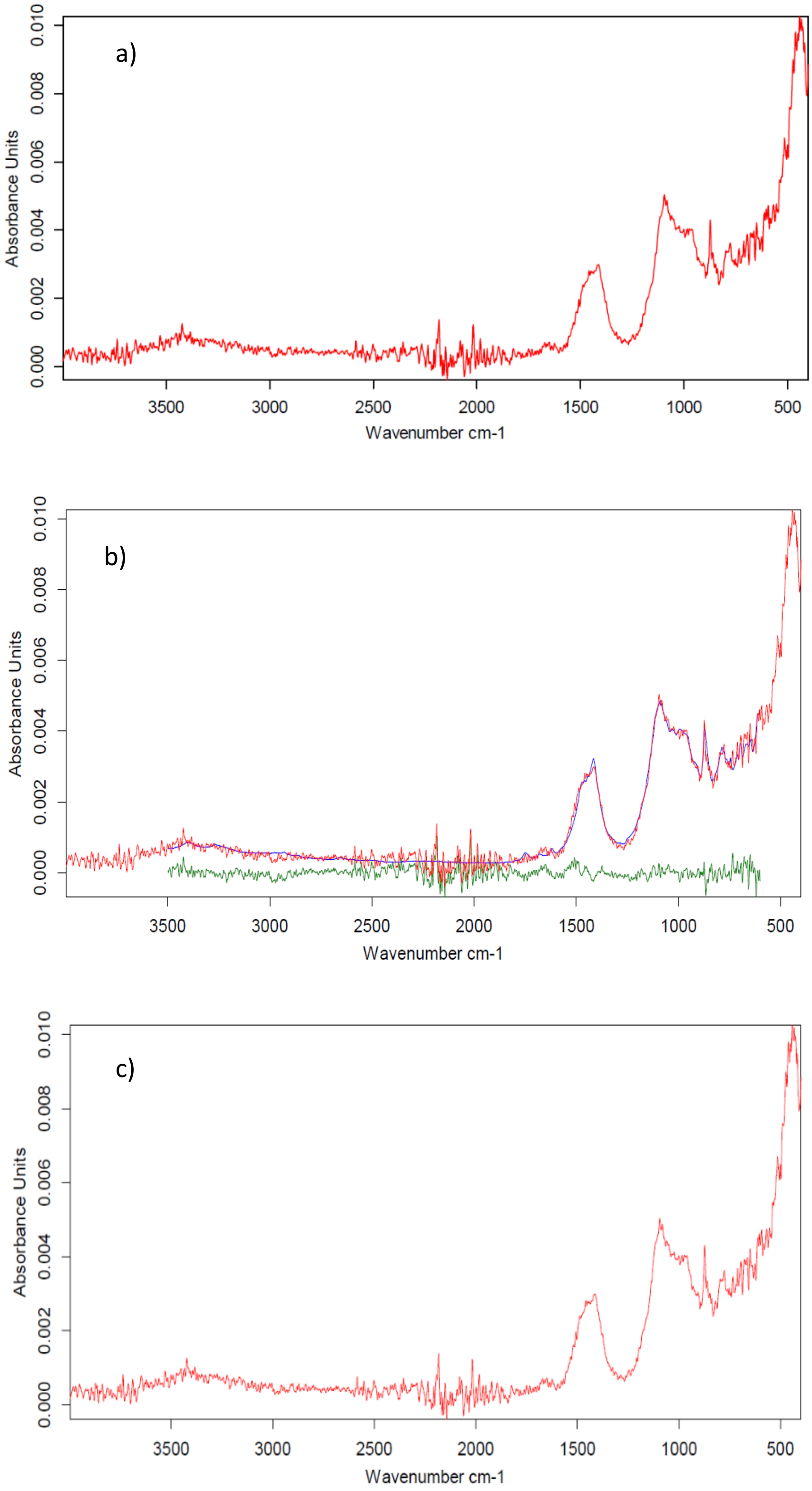

Figure 1 - IR spectrometry of samples with: a) sample with 20% fly ash; b) sample with 35% fly ash;c) sample with 40% fly ash (author's material)

The provided IR spectrum in **Fig.1 (b)** (red line with superimposed blue smoothing) of a hyper-pressed brick sample with 35% ash shows typical signs of cement hydration and active pozzolanic reaction, characteristic of high ash fraction systems. In contrast to the previous sample with 20% ash, the higher ash content (35%) leads to a more pronounced formation of secondary binding products in the later stages of curing. Bound water (3400-3500 cm^{-1} and 1600-1650 cm^{-1}):

The intense bands in these regions confirm the presence of hydroxyl groups (O-H) and water molecules within the hydrate neoplasms (C-S-H gel), indicating successful hydration. Carbonization (1400-1500 cm^{-1}) : The presence of CO_2^- peak indicates natural carbonization of Ca $(OH)_2$ on the surface of the samples. Binder gel formation (900-1100 cm^{-1}): The intense and broad Si-O peak is the main evidence for the formation of C-S-H gel, the main component providing strength. When the ash content is increased to 35% (second spectrum), a further decrease in the intensity of the calcium hydroxide peak (870-900 cm^{-1}) is expected compared to the sample with 20% ash.

In **Fig. 1 (c)**, the peak has high intensity and is shifted to low frequencies (960 cm^{-1}), which is a direct evidence for the formation of secondary, low-base and high-strength C-S-H gel due to ash. At 40% ash, this effect is maximized.

The SEM analysisis shown in **Fig.2 (a, b, c).**

SEM images confirmed the structural changes detected by IR spectrometry

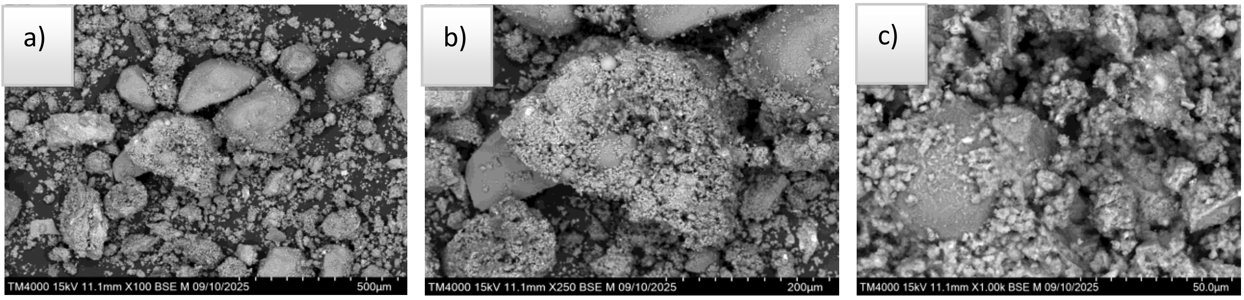

Figure 2 - Microstructure of specimens with fly ash application: a) 20% fly ash (28 days), b) with 35% fly ash (28 days), c) 40% fly ash (28 days) (author's material).

Early dates (7 days): the images are dominated by smooth, unaltered spherical ash particles surrounded by primary cement gel. Large Ca $(OH)_2$ crystals and relatively high capillary porosity are observed.

Long Timing (28-90 days): Ash spheres have a rough, "ruined"surface and are covered with a thin layer of secondary C-S-H gel (a product of the pozzolanic reaction). $Ca(OH)_2$ crystals are fragmented or completely absent, and the pores are filled with neoplasms. The overall microstructure appears much denser and more homogeneous, which explains the increase in strength and durability.

Thus, the SEM analysis convincingly confirms that the introduction of ash and slag waste into polystyrene concrete leads to the formation of an optimal, homogeneous and dense microstructure with a long curing time. This structure provides increased strength properties by increasing the proportion of binder (C-S-H), and also significantly increases the durability and performance properties of lightweight concrete, including its frost resistance and resistance to carbonation. Thus, the use of fly ash not only disposes of waste, but also acts as an active modifier to improve the structure of the composite material (**Takirova et al., 2025 & Abildaeva et al., 2022**).

The results confirm that the use of up to 40% of TPPs ash as raw material ensures effective utilization of industrial waste.

Thus, hyper-pressed brick with TPPs ash is a promising material with high physical and mechanical characteristics. Its high strength due to pozzolanic activity (verified by IR spectrometry), combined with low raw material costs, confirms its suitability in construction.

The images taken after curing show that the spherical ash particles are no longer inert inclusions, but have a cracked (rough) surface covered with new C-S-H gel formations. This is a direct evidence of the reaction on the ash surface.

Visual filling of capillary pores and the space previously occupied by $Ca(OH)_2$ crystals with secondary C-S-H gel leads to a general densification of the microstructure.

Thus, the research proves that the hyper compression method in combination with TPPs ash can produce a high strength material. Despite the delayed strength gain in the early stages, the long-term effect of the pozzolanic reaction - scientifically confirmed by IR spectrometry and SEM - ensures that the product meets the required grade (**Durdzi´nski et al., 2015 & Tolegenova et al., 2023**).

5 CONCLUSIONS

The conducted research has successfully demonstrated high efficiency and prospectivity of utilization of thermal power plant fly ash in the production of hyper-pressed building bricks. The following key conclusions were obtained on the basis of comprehensive analysis of physical-mechanical and structural-phase characteristics:

1.Hyper-pressed bricks with optimum ash content (up to 35-40%) achieved the required strength grade (≥M150) by long-term curing time (90-180 days). Although there was a reduction in strength in the early stages due to dilution effects, the long-term gain fully compensated for this deficiency.

2.The application of IR spectrometry allowed for the first time to confirm at the molecular level the curing mechanisms in hyper-pressed products with ash. Analysis of spectra showed that with increasing ash content (up to 40%) there is a decrease in the intensity of calcium hydroxide $Ca(OH)_2$ peak (870 cm^{-1}), which proves its active consumption by ash. The main binding gel peak C-S-H in the region 900-1100 cm^{-1} becomes more intense and shows a shift to low frequencies. This shift indicates the formation of a secondary, low-base and thus stronger C-S-H gel that compensates for the initial strength deficit from cement dilution.

3.The results of SEM analysis visually confirmed that at late curing time, an active reaction occurs on the surface of spherical ash particles. This leads to densification of the cement stone, which in turn explains the improved durability and reduced water absorption.

4.The use of TPP ash in hyper-pressing technology allows to achieve utilization of industrial waste and reduce energy consumption in comparison with roasting methods. Thus, the developed material is an ecologically and economically favorable building product.

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