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The challenges of reusing thermal power plant wastes to produce cellular concrete modified with wollastonite

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Abstract. This paper presents new approaches of reusing fly ash generated in thermal power plant in the manufacturing of cellular concrete. Therefore, the research novelty is to make a meaningful utilization of fly ash as a binder to improve cellular concrete properties. The study has showed that fly ash has pozzolana properties which can boost up mechanical strength, thermal insulation and durability of cellular concrete, which may lead to obtain high quality final product in comparison with traditional building materials. Moreover, utilization of fly ash facilitates both reduction of heat conductivity and reduction of concrete density. This properties make cellular concrete resistant to heat transfer. Physical, mechanical and thermal tests have been carried out during research. The study of type of dependence between cellular concrete durability and its mix design has a valuable practical importance since it supports to reach maximum durability in lightly consumption of binder. We may conclude that the utilization of fly ash in the amount of 295 kg/m^3, while the cellular concrete density is equal to 600 kg/m^3, allows to solve a number of problems such as damaging of human health and environment pollution and to develop energy efficient cellular concrete. The research included the results of cellular concrete mix flowability, density, moisture, strength properties and concrete grade equal to B2,5-B3,5 with a density of porous ash concrete equal to 600 kg/m³. The natural wollastonite was utilized in this research as a reinforcing material to improve the tensile stregnth of cellular concrete.

Keywords: cellular concrete product, utilization of thermal power plant waste, fly ash, mix design, binder, reinforcing material

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1. INTRODUCTION

Fly ash (FA), a by-product formed during the combustion of hard coal in thermal and power plants, presents significant issues concerning its management and disposal poses a significant challenge for nearly every country worldwide [1, 2]. This issue arises because each coal-fired power plant produces up to 12 tons of FA for every 100 tons of coal burned [3]. According to other data for every 4 tons of coal burned, 1 ton of FA is usually produced [4]. For this reason, huge amounts of this industrial waste are generated worldwide every year in the amount of up to 800 million tons [5]. Moreover, according to the conducted analyses, the estimated amount of production of these materials may in the early thirties of the 21-st century reach the value of 2100 million tons per year [6]. In addition, it should be noted that currently the two main countries of FA generation in the world—with production of 112 and 100 million tons respectively—are India and China [7]. The problem of ash and slag utilization in Kazakhstan requires a solution, as well. While in industrialized countries, the rate of industrial waste recycling are increasing, in Kazakhstan, it stands merely 1.4% or higher [8, 9]. Currently, most of the produced FA is processed in wet form and stored in ash tanks or stored in special landfills prepared for this purpose in areas adjacent to the power plant. Both solutions are harmful to the natural environment and result in the reduction and impoverishment of a significant area of land. In addition, FA stored in this way is not used for commercial purposes, but generates costs related to its maintaining [10]. In Czechoslovakia, fly ash is extensively utilized as a silica component, while mixed cement-lime serves as a binder in the production of porous concrete. In our context, we are particularly interested in the Hungarian experience with fly ash in porous concrete production, where the focus lies on manufacturing wall blocks and thermal insulation plates with densities ranging from 500 to 900 kg/m³, and strengths ranging from 2.0 to 7.5 MPa. Hungarian scientists believe these strengths to be quite commendable, attributing them to the inherent activity of fly ash, which significantly enhances concrete strength [11]. Conversely, it is worth emphasizing that fly ash (FA) offers significant potential as a partial replacement for ordinary Portland cement (OPC), mainly due to its beneficial physicochemical properties, fine grain size and quite good pozzolanic activity [12]. Consequently, the effective application of this by-product from coal combustion in the development of cement binders and concrete has been the focus of extensive research for many years [13-15]. Therefore, experiments and analyses are carried out regarding the properties of cement composites with FA as a replacement for cement part meeting the requirements of standards [15]. Studies have shown that the addition of fly ash, up to 20% of the total cement weight, can significantly improve the mechanical strength and fracture resistance of concrete composites under both basic and complex stress conditions [16]. Furthermore, it helps to reduce the harmful impacts of vibrations resulting from dynamic and impact loading [17, 18]. When used as a partial alternative to OPC, fly ash also demonstrates high synergistic efficiency in combination with other pozzolanic and nano-scale additives [19, 20].

The production of porous concrete, particularly through autoclave methods, using fly ash, is marked by its ease of technology, which, among other advantages, yields significant economic benefits. This is because ash is considerably cheaper than traditional sand and does not require grinding.

Based on previous studies, It has been observed that most existing research and practical implementations have concentrated on concrete mixtures containing up to 30% fly ash (FA) by cement weight [21,22]. In light of this, the current study focuses on examining a crucial physical characteristic that impacts the durability of concrete with FA. Specifically, the paper investigates the water absorption (wa) of concrete modified with varying levels of FA, aiming to evaluate its long-term performance [23, 24]. In addition to exploring this particular parameter, the study also seeks to contribute to solving broader challenges related to FA usage. Gaining deeper insight into further properties of FA could enhance its application in concrete technology and support the advancement of environmentally sustainable construction methods.

2.METHODS AND MATERIALS

In the production of porous concrete, both autoclaved and non-autoclaved, the type of raw materials has a significant impact on the performance properties of the finished products.

The main raw materials used in the research were Portland cement from the Shymkent Cement Plant, air-slaked lime, fly ash from a thermal power plant, construction gypsum, aluminum powder, natural wollastonite, and water.

Therefore, this study presents the results of an experiment investigating the formation and properties of autoclaved porous concrete, where fly ash is used to partially replace Portland cement. Furthermore, this paper assesses the impact of various key factors on the properties of porous concrete.

Table 1. shows the physical and mechanical properties of cement from the Shymkent plant.

Table 1. Physical and mechanical characteristics of cement.

Characteristic	Shymkent cement
Specific surface area, sm^2/g	3550
Normal consistency of cement paste, %	24,5
Initial setting time, hr.min	2-30
Final setting time, hr.min	3-40
Compressivestrength, MPa	34,3
Tensile strength, MPa	5,5

The cement's chemical and mineralogical compositions are provided in Table 2 and 3.

Table 2. Cement's chemical makeup, expressed as a percentage.

Name	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Losses during piercing
Shymkent cement	64,85	23,40	4,18	3,3	1,55	0,4	0,35

Table 3. Mineralogical composition of the cement in %.

Name	C_3S	C_2S	C_3A	C_4AF
Shymkent cement	55	22	5	15

The chemical and mineralogical compositions meet the requirements of CH-277, with the amount of tricalcium silicate being no less than 50%, and the amount of tricalcium aluminate is compliant as well.

Lime meets the requirements of [25, 26], with a slaking temperature of 60-75°C and a slaking time of 15-20 minutes. The activity of lime is 60-75%.

Aluminum powder PAP-1 was used as a foaming agent in laboratory studies, complying with [27].

The concrete mix was mixed with water that meets the requirements of GOST 23732.

Fly ash derived from the Ekibastuz coal basin is categorized as acidic in nature and was employed as a component rich in silica. The chemical composition of the fly ash is presented in Table 4.

Table 4. Chemical composition in % of fly ash.

Name of the fly ash	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Losses during piercing
Fly ash	56-62	25-27	4,9-7,5	3,4-4,0	1,1-1,3	1-3

The testing of the fly ash was conducted according to [27]. The ash content of the coal is up to 40%, with a specific surface area of 2800-3000 cm^2/g, residue on the 008 sieve at 210 g, and bulk density of 750 kg/m^3. The content of $SiO_2 + Al_2O_3 + Fe_2O_3$ is no less than 70%, SiO_2 content is no more than 3.5%, free CaO content is no more than 5%, MgO content is no more than 5%, and the loss

on ignition is no more than 5%. The uniformity of volume change was maintained. The moisture of the ash content falls within the range of 1% to 3%.

The fly ash morphology was studied using a X-ray microanalyzer. As shown in Fig. 1, the fly ash consists of clusters of particles of various sizes and shapes. A portion of the fly ash consists of perfectly spherical glassy particles, with diameters of 150 μm, the primary constituents are calcium combined with different compounds of aluminum, magnesium, silicon, and iron (Fig. 1, No. 1). A separate portion (Fig. 1, No. 2) is made up of foamed material containing irregularly shaped pores ranging from 15 to 25 μm, with a complex chemical structure that includes aluminum and silicon, mainly in the form of aluminum oxide and silicon carbide, along with small amounts of copper, osmium, iron, and zinc. The ash also contains irregularly shaped particles primarily composed of graphite (Fig. 1, No. 3).

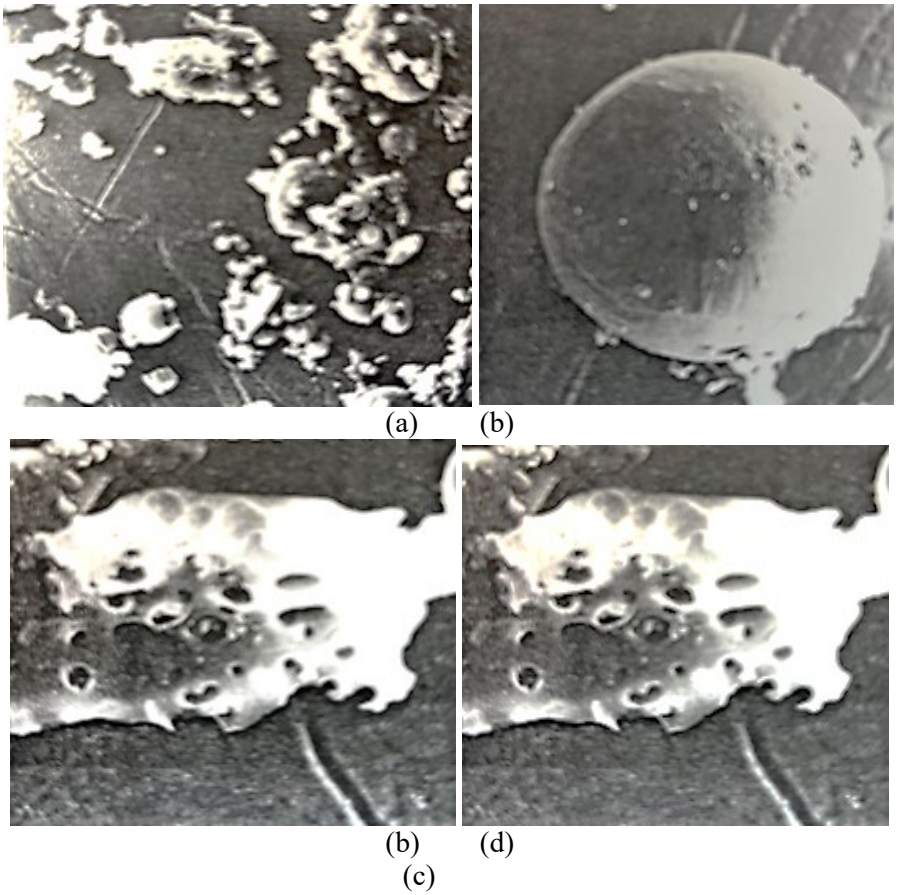


Fig. 1. Morphology of the fly ash: a. Overall view; b. a part of FA with perfectly spherical glassy particles; c. a part of FA with portions of foamed mass; d. a part of FA with irregularly shaped particles.

The rheological properties of the porous concrete mix were determined as follows:

The flowability was determined using the Suttard device, the plastic strength of the gas concrete mix and the kinetics of growth were established using a plastometer.

In our ongoing research, aimed at achieving durable and resilient autoclaved porous concrete with minimal cement consumption, we primarily rely on research findings showed that there are several possibilities to recycle waste materials as replacements for fine and coarse aggregates in concrete mixtures.

3. RESULTS AND DISCUSSIONS

The addition of fly ash as a siliceous component significantly affects the optimal water-to-solid (W/S) ratio, which is vital for determining the fundamental properties of gas ash concrete. This optimal ratio represents the weight proportion between water and dry ingredients at which the increase in the mixture's structural viscosity matches the gas release rate.

Insufficient W/S ratio leads to rapid increase in plastic viscosity, causing the gas ash concrete mixture to expand prematurely. This results in the accumulation of gas bubbles within the solution, when faced with resistance, gas bubbles break through the viscous mixture, leading to the formation of crack networks that significantly weaken the final strength. Under these circumstances, the gas ash concrete develops structural defects, and the effectiveness of gas utilization is notably reduced. Conversely, excessive W/S ratio leads to slow elevation in plastic viscosity, permitting the gas ash concrete mixture to maintain high flowability, leading to water separation, boiling, and settling as many gas bubbles rise to the surface. The rate of increase in plastic viscosity of a gas ash concrete mixture is contingent upon its water content and temperature. This phenomenon is mainly caused by the higher water content in the gas ash concrete mix, which promotes the development of a more consistent and improved porous structure. Nevertheless, with an increase in the mixture's temperature, the flowability of the gas ash concrete declines considerably (refer to Table 5).

Table 5. Effect of the water-to-solid ratio on the workability of the gas ash mixture.

W/T	Flowability of mixture, according to the Suttard viscosimeter (sm). Temperature 40^0C
0,50	11
0,55	19
0,60	24

This behavior is attributed to the accelerated hydration of lime and cement at higher temperatures, which leads to a more rapid absorption of water by the cementitious components. Generally, lime undergoes hydration faster than cement. As the water-to-solid (W/S) ratio increases, the disparity in hydration rates between lime and cement decreases, and at a W/S ratio of 0.75, the mixture's workability stabilizes and becomes independent of temperature variations.

Analysis of the pore structure in porous concrete shows that raising the W/S ratio under consistent conditions significantly alters the shape and distribution of pores. Specifically, the pore structure transitions from elongated, elliptical clusters—which tend to create localized stress points—to more evenly distributed, uniformly shaped pores with clearer boundaries. In macroporous concrete, spherical pores that typically form at higher W/S ratios result in more uniform porosity, thereby enhancing the material's overall strength (see Fig. 2).

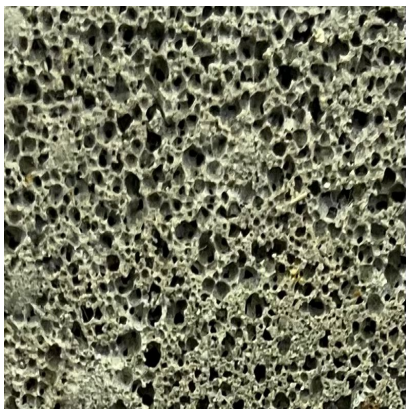


Fig. 2. The optimal structure of porous concrete with a density of 600 kg/m³ at W/C=0.6.

To summarize, raising the water-to-solid (W/S) ratio enhances the overall quality of the porous structure. A key advantage of a higher W/S ratio is the decrease in the mixture's viscosity, which improves its flowability and promotes the consistent development and even distribution of spherical pores throughout the volume. Nevertheless, an excessive W/S ratio may cause the mixture to separate, with surplus water collecting on the surface and spilling from the molds as the gas ash concrete expands, ultimately reducing the binder's reactivity. Although higher W/S ratios support good expansion, they also slow down the setting time, leading to a "boiling" effect due to gas emission and material settlement. Therefore, optimal W/S ratio values have been identified to prevent water separation on the surface and maintain structural stability without the need for additional gas-generating additives.

An increase in the W/S ratio from 0.6 to 0.65 reveals that while the mixture expands effectively at a ratio of 0.6, increasing it to 0.65—under otherwise identical conditions—results in partial water separation and accelerated expansion, which may cause the mixture to spill out of the molds. This also leads to a pore structure that is elongated and partially fused, differing markedly from the optimal configuration. To achieve the desired pore architecture in gas ash concrete, it is essential to manage temperature and mixture viscosity to ensure uniform distribution of spherical pores. Additionally, selecting a high-quality gas-forming agent is crucial. Coordinating the rate of structural viscosity growth with the timing of gas release is also key to achieving optimal performance.

Owing to the variation in pore sizes created by the gas, gas ash concrete may exhibit heterogeneity. The higher the quality of gas ash concrete is, the smaller and more evenly spread its pores are within the concrete. This results in uniform properties, such as strength, density, and thermal conductivity. This is achieved through the use of aluminum powder with smaller particle sizes. The powder is produced by mechanically vibrating aluminum together with ash to achieve the desired fineness. In industrial practice, the uniformity of the particle size distribution in the aluminum powder largely depends on the manufacturing processes employed by the supplier's facility.

In order to determine the most effective water-to-solid (W/S) ratio for mixtures containing fly ash, tests were conducted on gas ash concrete with a specified density of 600 kg/m³. The optimal ratio between the siliceous component and the binder (C) for achieving sufficient strength was found to be 1.2. Incorporating 3.0 kg/m³ of semi-aqueous gypsum ($CaSO_4 \cdot 0.5H_2O$) significantly improved the rheological behavior of the mixture, especially within the ideal temperature range of 40–45°C. The curing process followed a previously determined efficient steaming cycle of 3+6+3 hours at a controlled temperature of 90±5°C.

According to Table 3, a higher water-to-solid (W/S) ratio contributes to enhanced strength in gas ash concrete. In this research, the ideal W/S ratio for attaining peak strength was determined to be 0.60. Nevertheless, increasing the ratio to 0.65 results in partial water segregation, accelerated expansion, and slight spillage of the mixture along the mold edges.

The ideal water-to-solid ratio is determined by the mortar mix's water requirement, which, with a constant siliceous component to binder ratio (C), is influenced by the properties of the primary raw materials used. Utilizing complex vibration techniques allows for the reduction of mixture viscosity during expansion, leading to the formation of porous concrete with a well-developed macroporous structure at lower water-to-solid ratios. Studies conducted at the Research, Design, and Technological Institute of Concrete and Reinforced Concrete have revealed significant findings regarding the properties of porous concrete. It was observed that an increase in the water-to-solid ratio results in a twofold increase in compressive strength, whereas the dynamic modulus of elasticity (DMU) and the velocity of ultrasonic waves show only slight changes. This indicates enhanced elasticity in the material between pores and increased strength, largely due to improvements in the quality of the porous structure. This underlines the essential importance of the vapor space configuration in porous concrete.

To evaluate quality, the standard deviation of surface porosity is used, measured on a flat section of the porous sample through circular scanning. This deviation is determined using readings from an electric voltmeter equipped with an effective value pointer, enabling fast and efficient data collection. Table 6 displays the assessment of the macrostructural quality of gas ash concrete across various water-to-solid ratios.

Table 6. Impact of Water-to-Solid Ratio on the Strength Properties of Autoclaved Gas Ash Concrete.

Composition	W/TS	Flow according to the Suttard	Mixture temperature	Density	Compressive strength	Deviation of porosity value
		Sm	^{0}C	кg/m^3	MPa	Eph
1	0,5	11	40	600	2,5	0,175
2	0,55	13	40	640	3,0	0,163
3	0,6	24	40	700	3,5	0,133

Research analyzing the impact of porous structure on the performance of porous concrete reveals that as the water-to-solid (W/S) ratio increases from 0.50 to 0.60, the porosity deviation index (Eph) decreases from 0.175 to 0.133. This index, which represents the standard deviation of surface porosity, is obtained using a voltmeter equipped with an effective value pointer. A lower Eph value signifies enhanced macropore quality, characterized by well-rounded, uniformly distributed pores with minimal light dispersion. Such structural improvements lead to a notable increase in the strength of gas ash concrete.

Numerous researchers abroad have underlined the important impact of pore structure on the performance characteristics and service life of porous concrete materials. It has been established that, to obtain durable and high-strength gas ash concrete at any density, it is essential to synchronize the processes of gas evolution and mixture expansion with the development of plastic strength, ultimately leading to the attainment of a high-quality macroporous structure.

Our experiments demonstrated that using a cement-lime binder mixed in a 4:1 ratio, combined with up to 3 kg/m³ of semi-hydrated gypsum ($CaSO_4 \cdot 0.5H_2O$), and maintaining a water-to-solid ratio of 0.60 at a mixture temperature between 40 and 45°C, facilitates a balanced interaction between gas formation, expansion, and the development of plastic strength. These conditions allow for the production of high-quality autoclaved gas-ash concrete with an optimal porous structure. The ratio of the silica component to the binder is maintained at 1.2. Additionally, autoclaved gas-ash concrete of class B3 can be produced using no more than 200 kg/m³ of Portland cement at a density of 600 kg/m³.

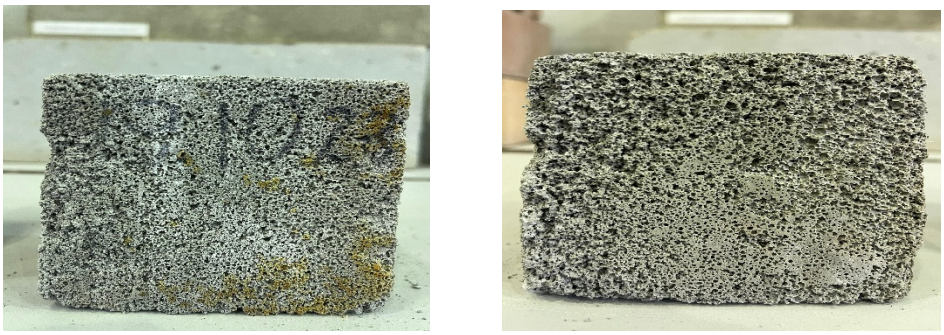
Further research into the impact of various silica components on porous concrete properties revealed that, in non-autoclaved gas-ash concrete production, gradually replacing sand with fly ash possessing a specific surface area of 2800–3000 cm²/g significantly increases strength from 0.83 MPa to 2.34 MPa. Complete replacement of sand with fly ash achieves the highest strength, enabling the production of non-autoclaved B3 grade gas-ash concrete using acidic fly ash sourced from coal combustion in the Ekibastuz coal basin.

Studies have demonstrated the possibility of replacing up to 50% of cement with lime without compromising strength, and in some cases, even enhancing the strength of porous concrete with a mixed binder. The substitution of cement with lime is typically motivated by both economic considerations and the improvement of the porous concrete mixture's properties, porous structure, and technical characteristics. Additionally, it allows for more efficient utilization of the gas-forming agent. The production of gas ash concrete enhances one of the key characteristics inherent in porous concrete – thermal properties – without incurring additional costs. Fly ash inherently exhibits reduced thermal conductivity, thereby enabling the enhancement of thermal insulation properties in gas ash concrete compared to sand-based porous concrete, as illustrated in Table 7. Moreover, the utilization of fly ash decreases the thermal conductivity and density of porous concrete, consequently bolstering its resistance to heat transfer overall. The utilization of ash in the production of autoclaved porous concrete holds the potential to address waste thermal energy disposal issues more comprehensively and substantially contribute to the improvement of regional ecology.

Table 7. Specified Parameters of Porous Concrete Properties.

Types of concrete	Concrete grade on average density	Coefficients			
		Heat conductivity, W/(m·^{0}C) no more than dry concrete		Vapor-permable, mg/(m·h·Pa) not less than manufactured concrete	
		with sand	with ash	with sand	with ash
Heat-insulating	D400 D500	0,10 0,12	0,09 0,10	0,23 0,20	0,20 0,18
Structural insulating	D500 D600 D700 D800 D900	0,12 0,14 0,18 0,21 0,24	0,10 0,13 0,15 0,18 0,20	0,20 0,17 0,15 0,14 0,12	0,18 0,16 0,14 0,12 0,11
Structural	Dl000 Dl100 Dl200	0,29 0,34 0,38	0,23 0,26 0,29	0,11 0,10 0,10	0,10 0,09 0,08

Further investigation into autoclaved gas concrete, subjected to treatment in an autoclave under a pressure of 0.8 MPa and a temperature of 174.5°C for a steaming period of 2+8+2 hours, consistently yields high strength indicators, resulting in gas ash concrete grades ranging from B2.5 to B3.5 at a density of 600 kg/m³ (Fig. 3).



(a) (c)

Fig. 3. The optimal structure of autoclaved porous concrete with a density of 600 kg/m³: a – front view; b – back view.

The findings indicate that the greatest strength achieved through autoclave treatment occurs when fly ash and lime are combined in a 1:1 ratio. This unexpected result can be clarified by analyzing the new compounds formed. At maximum strength, researchers observed that the phase composition features the disappearance of C2SH(A) and the appearance of lamellar crystals like tobermorite (C4S5H5) and xonotlite, alongside CSH(B). It is suggested that the decline in strength caused by exceeding the optimal fly ash content is primarily due to the dilution of the cementitious binder by unreacted ash particles.

Hence, we affirm the significant property that ashes exhibit increased hydraulic activity during complex lime-gypsum activation. Hence, harnessing the properties of acidic fly ash, such as those derived from coal combustion in the Ekibastuz coal basin, is vital for the production of autoclaved gas ash concrete. The effect of the siliceous component type on the properties of autoclaved porous concrete is presented in Table 8.

Table 8. The impact of the siliceous component type on the properties of autoclaved porous concrete.

Composition	Material consumption, kg per m³.					W/S	Workability of the mix	Density	Moisture	Durability	Concrete grade
	SPC	Lime	Sand	Ash	Al powder		sm	кг/м³	%	MPa	B
1.	196	49	295	0	0,416	0,6	25,5	604	16,0	3,42	2,5
2.	196	49	236	59	0,416	0,6	24,5	624	17,3	3,62	3,5
3.	196	49	147,5	147,5	0,416	0,6	19,5	606	16,3	1,10	3,5
4.	196	49	88,5	206,5	0,416	0,6	16,0	643	13,8	4,04	3,5
5.	196	49	59	236	0,416	0,6	15,5	622	15,4	3,82	3,5
6.	196	49	29,5	265,5	0,416	0,6	15,5	605	15,4	3,83	3,5
7.	196	49	0	295	0,416	0,6	15,0	600	16,8	3,96	3,5

The strength of autoclaved porous concrete with sand reached a maximum of 2.5 MPa, while with fly ash, it was 3.5 MPa. Investigation into plastic strength development aids in determining the curing period prior to surface finishing or cutting, using techniques such as concrete cutting. Reducing the duration of product holding before heat and humidity treatment allows for an increase in mold turnover cycles in production settings.

Based on practical experience, it is observed that the rate at which the strength of certain mixtures based on traditional silica sand increases slows down, leading to the need for scrapping off after 4-5 hours. To address this issue in production settings, special measures are taken to accelerate the rate of strength increase in porous concrete mixtures, such as sub-curing in a furnace at temperatures between 70-80°C or incorporating specific additives into the mixture. A study focusing on the development of plastic strength in a gas-ash concrete mixture (Figure 4) revealed that the plastic strength of the initial mixture (with proportions of C:L:FA at 2.0:0.5:2.95, corresponding to the tailored strength mixture of the second) progresses consistently.

It reaches a value of 0.012 MPa after 140 minutes, adequate for scrapping off, and attains a plastic strength of 0.02 MPa after 180 minutes from casting, enabling the cutting of gas ash concrete bodies into blocks. In this scenario, the established technological parameters achieved a balance between gas emission processes and plastic strength development, enabling the porous concrete mixture to acquire an optimal pore structure and minimal shrinkage. The density of the concrete approached the intended value of 600 kg/m³. The three-hour timeframe for cutting the body into blocks aligns with standards implemented at advanced factories for porous concrete production.

In the second mixture (with proportions of C:L:FA at 1.5:1.5:2.95 and an increased lime content), the development of plastic strength occurred much more rapidly. The concrete body solidified and attained plastic strength more vigorously, while the gas development process failed to keep pace with the increase in plastic strength. The gas bubbles generated were unable to fully counteract the rising viscosity of the mixture, resulting in a density of gas ash concrete at 700 kg/m³ instead of the intended 600 kg/m³. The cutting time of the mass into products, within 3 hours, complies with the standards adopted at leading plants for the production of porous concrete. In the second mixture (C:L:A; 1.5:1.5:2.95 with an elevated lime content), the increase in plastic strength occurred significantly faster. The mixture set and gained plastic strength much more intensely, and the gas generation process could not keep up with the increase in plastic strength. The forming gas bubbles were unable to completely overcome the increasing viscosity of the mix, resulting in a density of the porous ash concrete of 700 kg/m³ instead of the calculated 600 kg/m³.

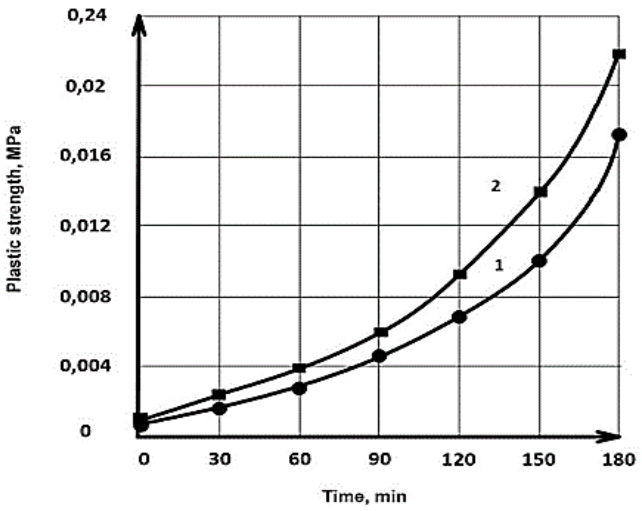


Fig. 4. Kinetics of plastic strength growth in porous ash concrete of different compositions: 1. C: L: A - 2,0:0,5:2,95; 2. C: L: A - 1,5:1,5:2,95.

The significant enhancement in plastic strength achieved through the use of fly ash allowed us to cut the concrete body into blocks after just 3 hours. This improvement can be attributed to the structural characteristics of fly ash itself. It has been observed that fly ash contains particles with a well-developed surface and a porous structure, which exhibit higher adsorption capacity, surface energy, and chemical activity.

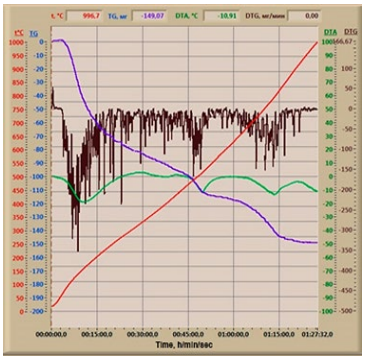
Therefore, the incorporation of fly ash in production processes eliminates the need for special measures to enhance plastic strength (such as using furnaces or special additives), which are not only economically unfavorable but also technologically cumbersome. Such measures often require additional equipment, making them inconvenient for production. In factory production of porous concrete, there are instances where challenges in controlling the rise of plastic strength necessitate the abandonment of using waste materials, despite their potential economic benefits (such as bauxite slurry, aluminum smelter production waste, and others). However, the utilization of fly ash from thermal power plants not only obviates the need for grinding the silica component but also eliminates the requirement for special measures to regulate the plastic strength rise during production. In our studies (Fig. 5) on radiographs of the porous ash concrete steamed according to the 2+8+2 hour regime at a temperature of 174±5°C, there are also peaks at d = 4.22, 3.90, 1.80, 2.60, and 2.41 Å, suggesting the presence of a hydrosilicate of the $C_2SH(A)$ type, which supports the findings of Yu.A. Butt.

Y.M. Butt further highlights that within the temperature range of 90 to 125°C, the enhanced solubility of quartz and the increased formation of compounds primarily result in the creation of low-basic, low-calcium silicates, such as tobermorite. Similarly, A.T. Baranov, in his studies, points out that when gas-ash concretes harden in autoclaves at temperatures around 170°C, the main products formed are low-basic calcium silicate compounds. The X-ray patterns of autoclaved porous ash concrete, steamed under a 2+8+2 hour regime at 0.8 MPa and 174.5°C, revealed the development of the following types, such as CSH(B) and a silicate mineral known as gyrolite. These are associated with the diffraction peaks at d = 3.04, 2.80, 1.82, and 1.67 Å for CSH(B), and d = 4.24, 3.36, 3.84, 2.85, 2.65, and 2.25 Å for a type of calcium silicate hydrate. The presence of small quantities of a type of calcium silicate hydrate in the autoclaved samples can be attributed to the high reactivity of the fly ash, which results from a large presence of amorphous, finely dispersed silica. It is worth highlighting that in the X-ray pattern of the autoclaved porous ash concrete, the peaks corresponding to gyrolite are more pronounced, suggesting a greater concentration of gyrolite compared to other calcium hydrosilicates.

We conducted a differential thermal analysis (DTA) to replicate the X-ray phase analysis. The thermogram analysis revealed endothermic effects in the low-temperature range for all samples, which are associated with the initial dehydration of calcium hydrosilicates. According to the literature, the

endothermic peak between 120-150°C is attributed to gyrolite, while the exothermic peak observed between 200-250°C is linked to CSH(B). Dehydration of C2SH(A) generally takes place within the temperature range of 420-480°C. Such endothermic effects have been noted, it is observed exclusively in the autoclaved samples and is related to the change in the stoichiometric ratio of CaO and SiO_2 oxides in the raw mixes.

In the high-temperature region of the thermogram, a significant difference is observed compared to the low-temperature section of the DTA. This can be attributed to the differences in the thermal behavior typical of gyrolite and CSH(B). In the thermograms of the steamed samples of the first and second compositions, a distinct endoeffect is observed at T=700-780°C, caused by the loss of constitutional water, and an exoeffect at T=820°C, associated with the crystallization of pseudowollastonite.



(a)

(b)

(c)

Fig. 5. Thermogram of lime-ash binder: a. A-5% lime/95% ash; b. B-10% lime /90% ash; c. C-15% lime/85% ash. Lime activity – 54%.

Consequently, physical and chemical investigations corroborate the disparity in the phase composition between autoclaved and non-autoclaved production of gas ash concrete. Notably, non-autoclaved gas concrete exhibits the presence of $C_2SH(A)$ in addition to hydrosilicates of the CSH(B) type, while gyrolite formation occurs in both cases, owing to the high activity and developed structure of fly ash.

The mechanical properties of autoclaved gas ash concrete differ from those of autoclaved gas concrete, including shrinkage deformations (Table 6). The shrinkage of autoclaved gas concrete measures at 0.6 mm/m, whereas for non-autoclaved gas concrete, it significantly increases to 2.89-2.91 mm/m, yet still meets the requirements outlined in [28] (Table 9).

Table 9. Properties of Autoclaved Gas Ash Concrete.

Mix-ture	Density, kg/m^3	W/S	Compressive strength, MPa	Concrete grade, B	Shrinkage according to [29], mm/m	DME, hPa	Freeze-thaw durability, 25 periodic time	Durability, damping, drying, $K_{Сж}^{CT} = \frac{R_{Сж}^{25}}{R_{Сж}^{0}}$
1	600	0,6	3,01	2	2,89	2,180	0,93	0,79
2	700	0,6	3,5	2	2,91	2,232	0,95	0,80

The heightened shrinkage observed in gas ash concrete can be attributed to the high moisture content of the samples post-steam curing, approximately around 30%, and the slower hardening processes compared to autoclaved variants. Following autoclaving, autoclaved gas ash concrete typically ceases strength development and, aside from carbonization processes, begins aging. Conversely, non-autoclaved concrete continues to develop strength even after steaming. Consequently, after 28 days of standard hardening, non-autoclaved concrete exhibited strengths 8-10% higher, and after 120 days, strengths were 18-20% higher than immediately post-steaming. This underscores the latent cement hardening potential (Fig. 6).

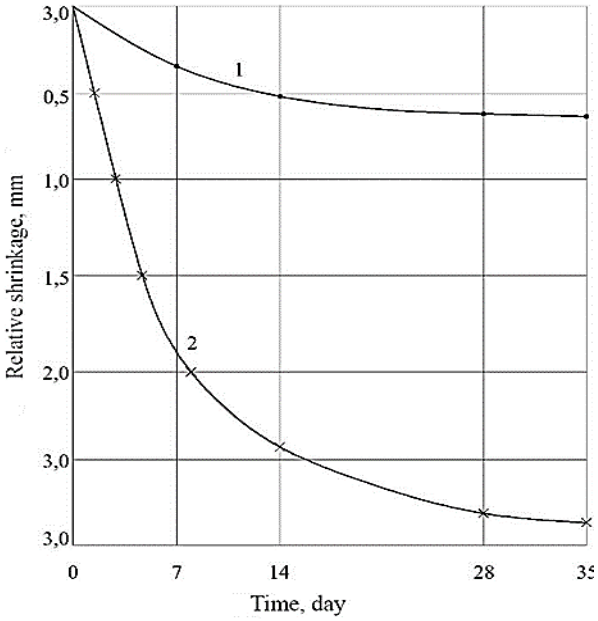


Fig. 6. Shrinkage deformations of porous concrete: 1. autoclaved porous concrete with fly ash; 2. non-autoclaved porous concrete with fly ash.

To mitigate shrinkage in non-autoclaved gas ash concrete, our research indicates that increasing the duration of temperature rise has negligible impact. While isothermal duration does show some positive influence on shrinkage, significantly extending it for shrinkage reduction purposes isn't recommended. Shrinkage can be alleviated by reducing mixing water, employing vibration techniques, or utilizing various surface-active agents. Additionally, evidence suggests that porous concrete based on ash is more susceptible to the effects of alternating wetting and drying, experiencing greater destructive impacts compared to alternating freezing and thawing cycles.

We conducted alternate wetting and drying tests on gas ash concrete with identical compositions and densities following the "Guidance on Test Methods of Porous Concrete Strength" developed by our team. The testing protocol involved 4 hours of wetting followed by 42 hours of drying at a temperature of 60±5°C, with subsequent cooling of the samples to 20±2°C. This regimen constitutes

one periodic cycle. The durability was assessed after 25 cycles of alternating wetting and drying, followed by compression strength testing and comparison with control samples. As shown by the data (Table 4), the compression durability coefficient (Cs) of 0.79 and 0.8 was lower than the frost resistance coefficient, which was 0.93 and 0.95, after 25 cycles of alternating freezing and thawing. These findings suggest that gas ash concrete is more vulnerable to the destructive effects of alternate wetting and drying compared to its resistance to freezing and thawing. The high frost resistance observed in autoclaved gas ash concrete can be attributed to its elevated porosity, particularly gas or macroporosity. This unique pore structure, characterized by spherical pores, functions as a buffer during the transition of water into ice, contributing to its high frost resistance. This emphasizes the importance of diligently safeguarding products made from fly ash against alternate wetting from rain and drying from exposure to the sun and wind. It is crucial to meticulously inspect the quality of the finishing or plaster coat and adhere to the instructions for finishing surfaces made of porous concrete. Table 10 presents data on how the thermal conductivity of autoclaved gas-ash concrete depends on its moisture content and density.

Table 10. The Effect of Density and Moisture Content on the Thermal Conductivity Coefficient of Autoclaved Gas-Ash Concrete.

№	Density kg/m^3	Water content in %, thermal conductivity Wt/m·^{0}C			
		0	5	10	20
1	500	0,10	0,15	0,19	0,31
2	600	0,13	0,17	0,21	0,33
3	700	0,15	0,20	0,26	0,37

The autoclaved gas-ash concrete developed by us, with a density of 600 kg/m³ and 0% moisture content, had a thermal conductivity coefficient of $\lambda = 0.130$ W/m·°C. When stored in dry, hot climates for 10 days, the humidity of our products, within 30%, will decrease significantly by 10-15% compared to the selling temperature. The established technological attributes of autoclaved porous concrete enable us to endorse the material for production as an enclosure product that meets all the requirements for strength, shrinkage deformations, thermal conductivity, and durability outlined in [28].

4. CONCLUSIONS

The feasibility of producing autoclaved porous ash concrete utilizing fly ash sourced from thermal power plants and natural wollastonite as a siliceous component, employing cutting-edge technology to achieve a density of 600 kg/m³, has been both theoretically analyzed and experimentally validated. The optimal technological parameters for manufacturing robust and resilient autoclaved porous ash concrete have been determined through experimentation: a cementing substance composition comprising 80% slag Portland cement and 20% lime, with a water-to-solid ratio of 0.60. The ratio of silica component to binder (C) is fixed at 1.2, with 1.2% semi-aqueous gypsum ($CaSO_4 \cdot 0.5H_2O$) added by binder weight, along with 5-8% wollastonite, to enhance the rheological properties of the mixture. The temperature during mixing is maintained at 40-45°C.

It has been observed that the plastic strength growth kinetics of the gas-ash concrete mixture enable the mass to be cut into products after just 3 hours, aligning with contemporary porous concrete production techniques, instead of the previously required 6-8 hours. In addition, the acidic fly ash derived from combustion in the Ekibastuz coal basin demonstrates high reactivity as a siliceous component, maintaining stable properties and containing a substantial glass phase of 60-65%, which makes it a valuable material for the manufacture of autoclaved porous concrete.

Utilizing fly ash from thermal power plants, with a specific surface area of 2800-3000 cm²/g, allows for the elimination or substantial reduction of the energy-intensive grinding process in the technological cycle. Moreover, it obviates the need for special additives and other measures to stabilize plastic strength. Incorporating fly ash at a rate of 295 kg/m³ into gas-ash concrete with a density of 600 kg/m³ addresses the issue of widespread disposal while significantly enhancing environmental conditions.

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