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Resource-Saving Technology for the Production of Three-Layer Exterior Panels with a Thermal Insulation Layer of Highly Porous Polystyrene Concrete

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Abstract: The study presents the development and investigation of a new technology for the production of three-layer exterior panels with a thermal insulation layer of highly porous polystyrene concrete. As a result of the research, it was found that the existing technology requires more manual labor compared to the proposed one, for example, the installation of connections, the laying of polystyrene plates, and the sealing of joints between the plates. The proposed technology will reduce the production time of each panel by 20 minutes, which increases the productivity of the production line and reduces the labor intensity of manufacturing the product. The thermal insulation layer of polystyrene concrete is non-flammable, while polystyrene plates are combustible materials. The air-entraining additive, combined with steam curing, allows for an increase in porosity up to 4.5% without reducing strength. Experimental studies in laboratory conditions revealed that the use of a plasticizer can reduce the amount of mixing water by more than 10%.

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1 INTRODUCTION

Currently, in the era of resource-saving technologies and materials, the main priorities in residential construction are economic efficiency, high construction rates, and the durability of buildings and structures. To enhance these aspects, innovative materials that comply with the regulations and standards of design and normative documentation are being used (Lopes, Vicente, Azenha, Ferreira, 2018). The use of such materials leads to a reduction in the overuse of construction raw materials and a decrease in the labor intensity of the construction process, which positively affects the pricing efficiency of the structure (Sizov, Pavlovskaya, 2022; Blazhko, 2015; Tazhentayeva, Ahmed, 2024). At the same time, the most important role in maintaining overall comfort inside a building, as well as ensuring the efficiency of buildings and structures, is assigned to wall panels (Gorin, Ryabchun, Kulik, 2019; Akkoc, Karagoz, Bicak, Sirkecioglu, 2022; Le Duong, Pásztory, 2021). A series of studies has been conducted in this field. For instance, in (Ravindrarajah, Tuck, 1994), the properties of hardened concrete containing granules of chemically treated polystyrene were experimentally studied in the mid-90s, where it was found that the strength, rigidity, and chemical resistance of concrete with a polystyrene aggregate of constant density are influenced by the water-to-cement ratio. As a result, empirical equations were developed that link force and impulse velocity, and predict the modulus of elasticity based on its strength (Sun, Li, You, Bu, Yu, Yan, Liu, Zhang, Chen, 2022). Modern research also showed the wide application of polystyrene in enclosures, with (Meddage, Chadee, Jayasinghe, Rathnayake, 2022) providing both theoretical and experimental evidence of the high efficiency of panels containing polystyrene in hot climates. The comprehensive study resulted in findings indicating a reduction in lifecycle costs, CO_2 emissions, and operational energy consumption (Meddage, Jayasinghe, 2022). Additionally, it was shown that the production of polystyrene concrete is environmentally clean, as it reduces the waste content of polystyrene, which does not decompose naturally (Leão, Spini, de França, Costa, 2024; Prasittisopin, Termkhajornkit, Kim, 2022; Xiang, Song, Shu, Li, Qiu, Gu, 2022). A similar efficiency of using polystyrene in external enclosure structures as a thermal insulation material in cold climates was covered in (Rakhimova, Zhangabay, Samoilova, Rakhimov, Kropachev, Stanevich, Karacasu, Ibraimova, 2024; Zhangabay, Tagybayev Utelbayeva, Buganova, Tolganbayev, Tulesheva, Jumabayev Kolesnikov, Kambarov, Imanaliyev, Kozlov, 2023), where the application of polystyrene insulation demonstrated effectiveness ranging from 5 to 21% depending on the type of structure and insulation thickness (Tagybayev Utelbayeva, Buganova, Tolganbayev, Tulesheva, Jumabayev Kolesnikov, Kambarov, Imanaliyev, Kozlov, 2023; Tagybayev, Baidilla, Sapargaliyeva Shakeshev, Baibolov, Duissenbekov, Utelbayeva Kolesnikov, Izbassar, Kozlov, 2023; Kudabayev, Mizamov, Zhangabay, Suleimenov, Kostikov, Vorontsova, Buganova, Umbitaliyev, Kalshabekova, Aldiyarov, 2022; Tagybayev, Zhangabay, Suleimenov, Avramov, Uspenskyi, Umbitaliyev, 2023). However, these studies only used one type of insulation with a uniform structure, such as foam glass, without a variable pore size analysis. Considering the thermal insulation efficiency in different conditions, as well as the rapid construction of designed buildings, various studies are currently being conducted to improve thermal qualities and reduce construction costs using different types of additives (Stanevich, Bulyga, Vyshar, Girnis, Rakhimova, 2022; Blazejczyk, Jastrzebski, Wierzbicki, 2020; Coquard, Quenard, Baillis, 2018; Hasanzadeh, Azdast, Doniavi, Eungkee Lee, 2019), which mainly reflect improvements in thermal efficiency and cost reduction. The use of such additives can also achieve energy efficiency by creating larger air spaces through increased porosity. This relates to the optimization of panels by applying high porosity polystyrene concrete technologies through the use of various additives (Samoilova, Rakhimov, Rakhimova, Zhangabay, 2024; Plotnikova, Pichugin, Verigin, 2012). However, when optimizing multilayer panels with the use of polystyrene, it is necessary to consider such criteria as energy efficiency and strength. While a high number of pores can achieve energy savings (Vyshar, Stolboushkin, Rakhimova, Stanevich, Rakhimov, 2023; Kathiravel, Weerasinghe, Jayasinghe, 2024; Zhangabay, Tursunkululy, Ibraimova Abdikerova, 2024), it may not meet the strength requirements (Zhangabay, Kudabayev, Mizamov, Imanaliyev, Kolesnikov, Moldagaliyev, Merekeyeva, 2023; Zhangabay, Zhangabay, Utelbayeva, Tursunkululy, Sultanov, Kolesnikov, 2025; Zhangabay, Oner, Rakhimov, Tursunkululy, Abdikerova, 2025; Zhangabay, Tursunkululy, Utelbayeva, Abdikerova, Sultanov, 2025) established by regulatory documents.

The review of existing studies indicates the presence of a number of issues in earlier research, as

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there is a lack of comprehensiveness in the results obtained. In some cases, for example, research is conducted on thermal efficiency and cost-effectiveness using different additives and solutions, while in others, the focus is on the strength characteristics of similar structures. It should be noted that such an approach is not practically applicable in real life. Considering these circumstances, the goal of this work is to develop an energy-efficient, highly porous three-layer panel using a newly developed technology.

2 MATERIALS AND METHODS

2.1 The following materials were used for the production of the wall panel:

- Portland cement I 42.5B (M500D0), with the specific effective activity of natural radionuclides for raw materials: A_{eff}(cement) = 57 Bq/kg, from JSC "Central Asia Cement";
- Blast furnace slag as a composite binder for cement;
- Air-entraining additive;
- Superplasticizer with water-reducing properties;
- Crushed stone of fraction 5-20 (Keregetas quarry);
- Sand and gravel mixture (Shakhan quarry);
- Mixing water.

The chemical composition of the cement and slag is shown in Table 1. Blast furnace slag is a chemically active by-product of the metallurgical industry and reacts with cement and additives.

Table 1: Chemical composition of Portland cement and blast furnace slag.

Binding Material	SiO_2	Al_2O_3	CaO	MgO	Cl
Portland cement M500D0	23.37	4.98	60.38	1.13	0.003
Blast furnace slag	36.5	13.95	38.74	9.47	0.038

Due to the high content of calcium, silicon, and aluminum oxides (SiO_2, Al_2O_3, CaO), concrete containing blast furnace slag becomes more resistant to aggressive environments (alkalines, salts, and acids).

Figure 1 schematically shows the product made using the proposed technology.

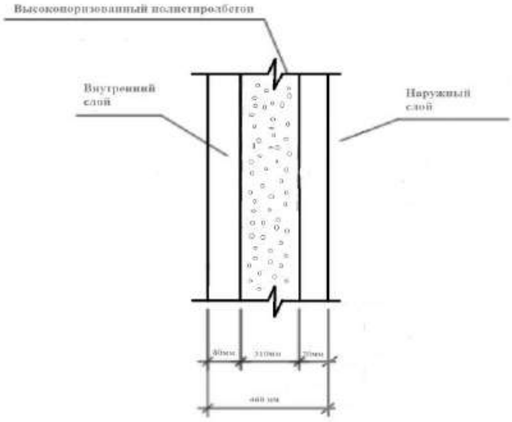

Figure 1: Wall panel with a thermal insulation layer of highly porous polystyrene concrete.

The mechanical and thermal-physical properties of all layers of the proposed panel were studied in an accredited laboratory and are as follows (Table 2):

Property	Inner Layer	Highly Porous Polystyrene Concrete	Outer Layer
Thermal conductivity, mW/m°C	1.74	0.095	1.74
Vapor permeability, mg/m·h·Pa	0.03	0.087	0.03
Compressive strength grade	B30	B1.5	B30

All the parameters of the studied panel meet the standards of the regulatory documentation [24, 25].

2.2 At the precast concrete plants, the products are manufactured using the following technology (Figure 2):

1. The pallet with the molds for the products is cleaned and lubricated at the cleaning station.
2. At the same time, workers fabricate the reinforcement cages for the products.
3. After the cleaning station, the pallet is sent to the reinforcement station, where the finished volumetric reinforcement cages are installed into the molds.
4. After the reinforcement assembly process is completed, the assembly and mold preparation are checked by the quality control department.
5. After the reinforcement assembly is completed, the pallet is sent to the concreting

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station, where the concrete mixing unit prepares the required amount of concrete mixture and unloads it into the concrete distributor located at the concreting station. Cement is stored in silos. Coarse and fine aggregates are stored in bins, which are fed from the main open warehouses. Mixing water is supplied from a reservoir, and additives are stored in sealed tanks.

6. After the mixture is placed, vibration compaction is carried out.

7. Then, the insulation plates (polystyrene) are installed.

8. Next, the second layer of concrete is applied. The surface of the products is then smoothed.

9. The pallet with the molded products is sent along the line to the thermal-moisture processing chamber.

10. After the required time for achieving formwork strength, the pallet is removed from the chamber, and the products are demolded.

11. After quality control inspection, the products are shipped to the finished goods warehouse.

12. The released pallet is sent for cleaning and lubrication, starting the new cycle.

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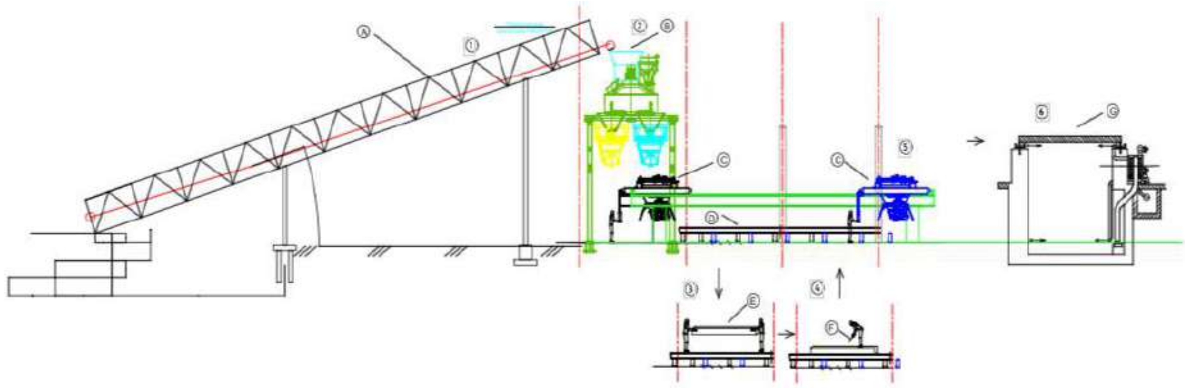

Figure 2: Technological diagram of the existing technology for the production of three-layer wall panels (1 – raw material feeding for mixing in the concrete mixer, 2 – mixing of components in the concrete mixer and delivery of the concrete mixture into the mold using the concrete distributor, 3 – laying of the polystyrene plate, 4 – installation of connections, 5 – laying of the second layer of heavy concrete mixture, 6 – thermal-moisture processing of the products; A – conveyor for feeding materials into the concrete mixer, B – concrete mixer, C – concrete distributor, D – product molding station, E – polystyrene plate, F – connections, G – thermal-moisture processing chamber).

The existing technology requires some manual labor compared to the proposed one, such as the installation of connections, laying of the polystyrene plate, and sealing of joints between the polystyrene plates (Figure 3):

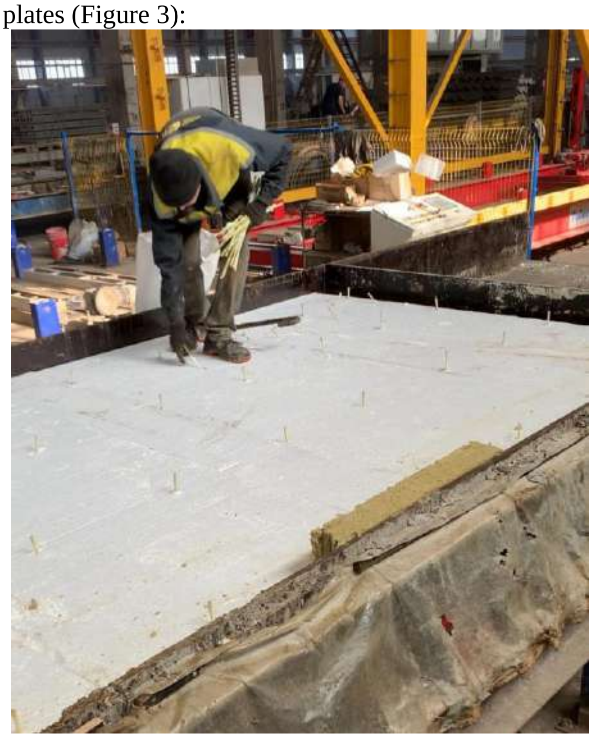

Figure 3: Installation of connections onto the polystyrene plate.

1. A reinforcement mesh is installed onto the mold with formwork, after which the heavy concrete mixture is applied.
2. After the mixture is laid, it is compacted for 30 seconds.
3. The pallet then moves to the pre-curing chamber until the concrete mixture begins to set, for 10 minutes, and a new pallet replaces it.
4. After 10 minutes, a mixture of light polystyrene concrete is applied to the just-set heavy concrete layer.
5. After laying the two layers of concrete, the pallet is sent back to the pre-curing chamber for 10 minutes to set the light concrete.
6. After the light concrete has set, a reinforcement cage is installed, and a second layer of heavy concrete is poured, similar to the first layer.
7. The second layer of heavy concrete is compacted using a submerged vibrator.
8. The finished wall panel is sent to the thermal-moisture processing (TMP) chamber for 12 hours, where it undergoes all stages of isothermal heating.

3 RESULTS AND DISCUSSION

3.1 The proposed technology for manufacturing wall panels with a thermal insulation layer of highly porous polystyrene concrete (Figure 4).

The technology for manufacturing wall panels with a thermal insulation layer made of polystyrene concrete (Figure):

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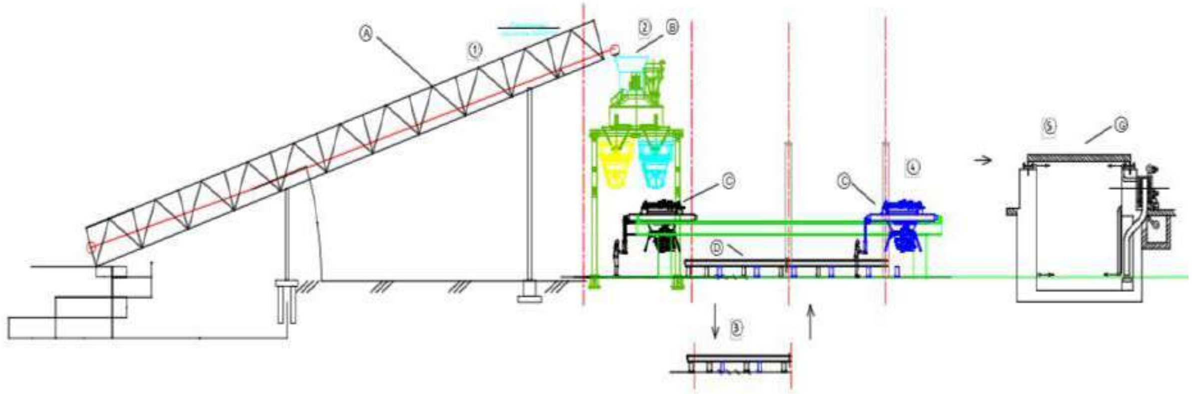

Figure 4: Technological diagram of the proposed technology for the production of three-layer wall panels (1 – raw material feeding for mixing in the concrete mixer, 2 – mixing of components in the concrete mixer and delivery of the concrete mixture into the mold using the concrete distributor, 3 – pre-curing station, 4 – laying of the second layer of heavy concrete mixture, 6 – thermal-moisture processing of the products; A – conveyor for feeding materials into the concrete mixer, B – concrete mixer, C – concrete distributor, D – product molding station, G – thermal-moisture processing chamber).

The comparative time characteristics of the existing and proposed technologies are provided in Table 2.

Table 2: Comparative time characteristics of the existing and proposed technologies.

No.	Existing	t, min	Proposed	t, min
1	Mold installation	10	Mold installation	10
2	Installation of reinforcement mesh	3	Installation of reinforcement mesh	3
3	Laying of heavy concrete	5	Laying of heavy concrete	5
4	Compaction of heavy concrete	1	Compaction of heavy concrete	1
5	Cutting of polystyrene plate for laying on heavy concrete layer	15	Laying of thermal insulation layer	5
6	Laying of polystyrene plate	5	Installation of reinforcement cage	5
7	Installation of connections for bonding polystyrene plate with concrete (manual)	7	Laying of heavy concrete	5
8	Installation of reinforcement cage	5	Compaction of heavy concrete	1
9	Laying of heavy concrete	5	Thermal-moisture processing (TMP)	720
10	Compaction of heavy concrete	1		
11	Thermal-moisture processing (TMP)	720		
TOTAL, min		777		755

The process of laying and molding concrete layers is carried out using a concrete distribution bunker (with two sections) (Figure 3).

It is important that the concrete structure does not form before passing through the TMP, as due to temperature fluctuations, the volume of the concrete will be in a stressed state, which may lead to disruption of the microstructure and the formation of cracks. This also increases the bond between the layers of light and heavy concrete.

Figure 5: Concrete distributor for molding products.

The light concrete mixture is not compacted, as it is important to achieve high porosity. The superplasticizer in the mixture prevents further shrinkage of the light concrete.

Panel heat treatment regime:

1) Heating to a temperature of 60°C – 3 hours;
2) Soaking the products at 60°C – 12 hours;
3) Soaking the products in the chamber while lowering the temperature – 4 hours.

The total curing time for the products is 19 hours.

The first stage of heat treatment is characterized by the product absorbing additional moisture due to the condensation (cooling) of steam when it comes into contact with the product and the mold edges. During heating, the components of the concrete, especially water and air, expand because they have the highest thermal expansion coefficients. In the first period, a decrease in pressure is not allowed, as this will lead to the evaporation of water and may cause the finished product to break.

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In the second period, when the temperature reaches the set values, the formation of calcium silicate hydrates (C-S-H) occurs, which are the fundamental factors in the formation of the concrete structure. The processes occurring with the concrete in the autoclave obey thermophysical laws that influence its structure.

During the pressure reduction process, it is important to control the rate of pressure reduction to prevent damage to the concrete. Cooling occurs slowly due to the low heat transfer.

Table 3: Comparative indicators of wall panel manufacturing technologies.

No.	Indicator	Existing Technology	Proposed Technology
1	Layer bonding	Connections are required	Dense layer adhesion
2	Time from start to end of production	19.5 hours	19.5 hours
3	Strength of the insulation layer	-	B1.5
4	Thermal insulation functions of the product	Cold bridges arise due to incomplete bonding of the polystyrene plate with the concrete	No cold bridges due to bonding of two types of concrete
5	Fully automated process	Workers are required to install connections and polystyrene plates	Yes
6	Flammability of the insulation layer	G4 (highly flammable)	G1 (fire-resistant)
7	Toxicity of the insulation layer	Toxic	Less toxic due to lower polystyrene content

The bonding of the layers refers to the density of their adhesion to each other. Due to the smooth surface of the polystyrene layer, its adhesion to the concrete occurs only due to connections. However, the polystyrene does not adhere uniformly to the concrete, so this type of construction often has cold bridges, which lead to heat loss in buildings and structures (Figure 7).

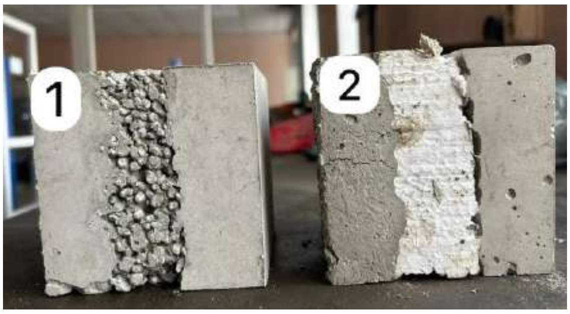


Figure 7: Comparison of panel models with a layer of high-porosity polystyrene concrete (1) and with a layer of EPS (2).

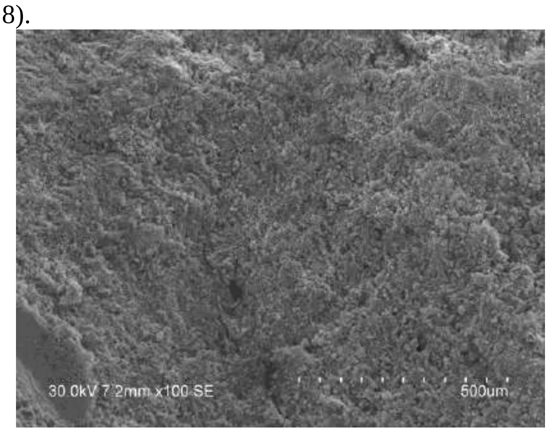
3.2.1 The strength properties of both types of concrete were tested on a hydraulic press. For the study, a mixture of light and heavy concrete was selected, and after curing in the thermal-moisture processing chamber, cubes with dimensions of 10x10x10 were tested on the press.

Table 4: Strength characteristics of concrete samples.

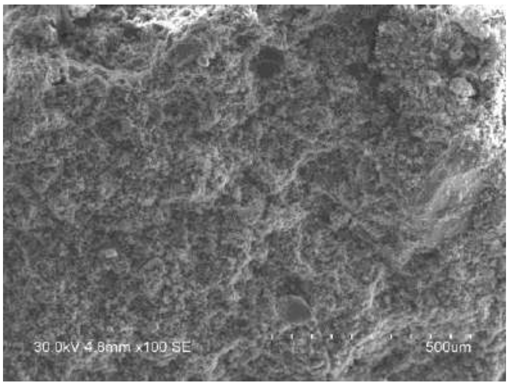
Concrete Class	Standard Requirement	Actual result
B30	38.4 MPa	39.0 MPa
B1.5	2.7 MPa	2.8 MPa

The actual results of the tested samples meet the standards of the regulatory documentation.

3.2.2 In the panels being produced, high-porosity polystyrene concrete is used as the thermal insulation layer. This means that, in addition to polystyrene in its composition, additional pores in the cement matrix are formed due to the additive introduced. The aeration of the concrete occurs as a result of chemical reactions, during which air bubbles are formed in the concrete mixture (Figure 8).



a



b

Figure 8: Microphotographs at 100x magnification of cement stone samples without air-entraining additive (a) and with its addition (b).

In Figure 8, the uniform distribution of closed pores of various sizes, which formed after the addition of the air-entraining additive, is clearly visible. Its introduction into the concrete mix will enhance the thermal insulation properties of the concrete, as well as its sound and noise insulation.

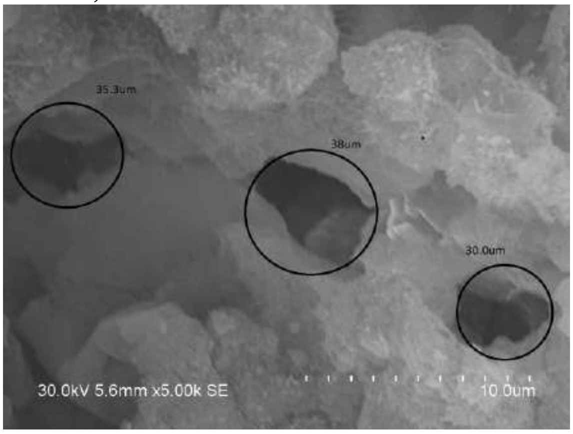


Figure 9: Microphotograph at 5000x magnification of a cement stone sample, showing the pore sizes .

The porosity of the concrete mixture was investigated according to [9] using the compression method. A porometer was used for the study (Figure 10).

Figure 10: Porometer for determining the porosity of the concrete mixture.

It was practically observed that the use of the air-entraining additive increases the volume of air entrained by about 1.5%. Additionally, in work [5], it was found that steam curing of concrete can increase its porosity by nearly 3%. An increase in the volume of entrained air by more than 5% results in a significant reduction in concrete strength.

Experimental tests under laboratory conditions showed that the use of a plasticizer can reduce the amount of water by more than 10%.

Using a scanning electron microscope (SEM) Prisna E, photos were taken of the bond between polystyrene granules and cement paste, showing that the granules are fully incorporated into the pores of the cement paste (Figure 11).

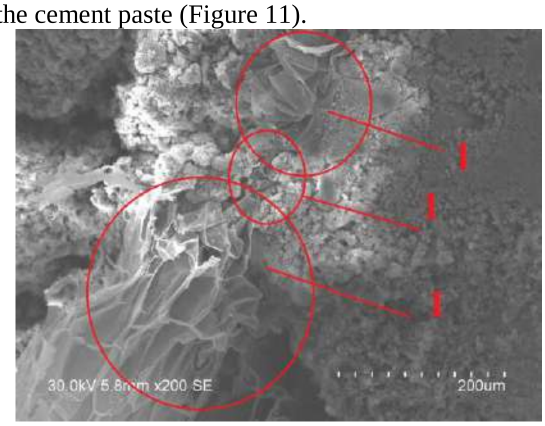


Figure 11: Bonding of polystyrene with cement paste (1 – Polysterene granules).

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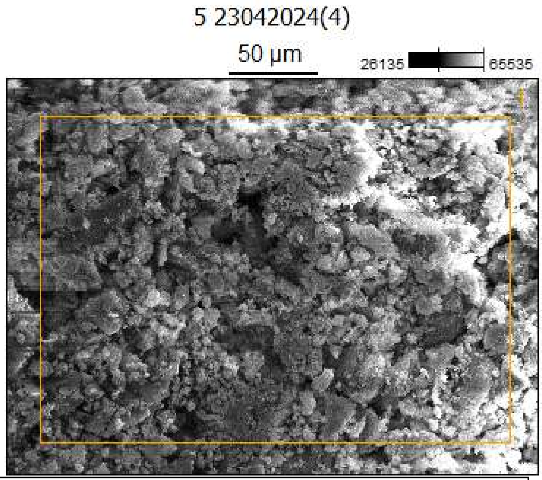
When conducting EDX (Energy Dispersive X-ray) analysis of two cement paste compositions (the proposed composition with additional porosity and the control sample), the results showed approximately identical chemical compositions. However, the thermal insulation properties of the proposed composition are higher than those of the control sample, due to the additional porosity of the cement paste.



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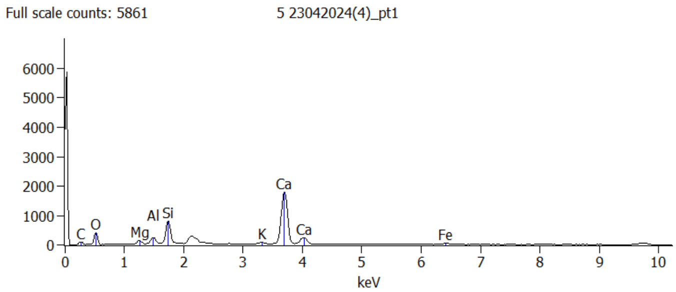

Weight %

	C-K	O-K	Mg-K	Al-K	Si-K	K-K	Ca-K	Fe-K
5 23042024(4)_pt1	6.60	46.12	2.26	3.62	11.11	0.56	28.51	1.22

Weight % Error (+/- 1 Sigma)

	C-K	O-K	Mg-K	Al-K	Si-K	K-K	Ca-K	Fe-K
5 23042024(4)_pt1	±0.37	±1.16	±0.15	±0.10	±0.18	±0.05	±0.28	±0.12

Atom %

	C-K	O-K	Mg-K	Al-K	Si-K	K-K	Ca-K	Fe-K
5 23042024(4)_pt1	11.44	60.03	1.94	2.79	8.24	0.30	14.81	0.46

Atom % Error (+/- 1 Sigma)

	C-K	O-K	Mg-K	Al-K	Si-K	K-K	Ca-K	Fe-K
5 23042024(4)_pt1	±0.64	±1.50	±0.13	±0.08	±0.13	±0.03	±0.15	±0.04

Figure 12: EDX (Energy Dispersive X-ray) analysis of the proposed composition.

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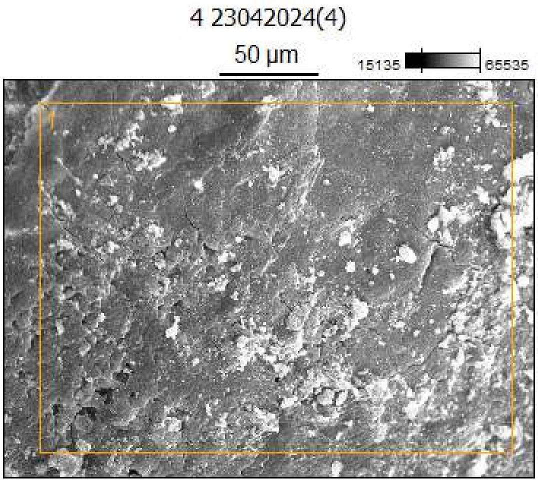

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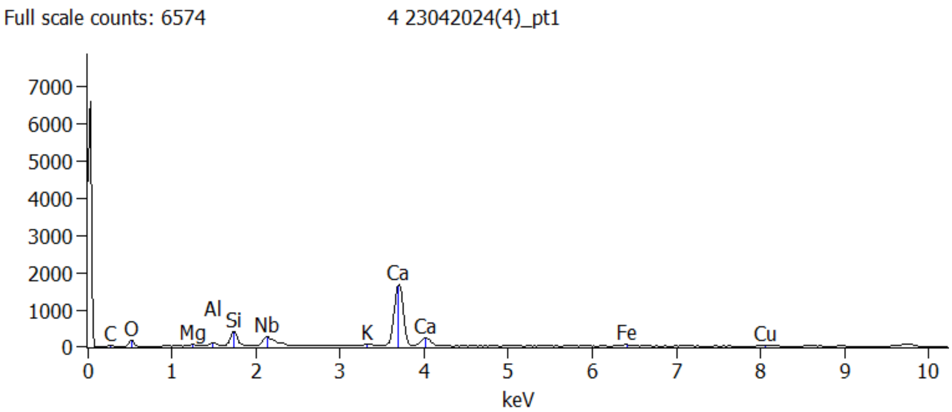

Weight %

	C-K	O-K	Mg-K	Al-K	Si-K	K-K	Ca-K	Fe-K	Cu-K	Nb-K
4 23042024(4)_pt1	3.43	35.49	1.06	1.81	8.96	0.78	42.57	2.21	3.32	0.38

Weight % Error (+/- 1 Sigma)

	C-K	O-K	Mg-K	Al-K	Si-K	K-K	Ca-K	Fe-K	Cu-K	Nb-K
4 23042024(4)_pt1	±0.27	±1.48	±0.12	±0.11	±0.22	±0.07	±0.42	±0.19	±0.29	±1.81

Atom %

	C-K	O-K	Mg-K	Al-K	Si-K	K-K	Ca-K	Fe-K	Cu-K	Nb-K
4 23042024(4)_pt1	6.94	53.95	1.06	1.63	7.76	0.48	25.83	0.96	1.27	0.10

Atom % Error (+/- 1 Sigma)

	C-K	O-K	Mg-K	Al-K	Si-K	K-K	Ca-K	Fe-K	Cu-K	Nb-K
4 23042024(4)_pt1	±0.54	±2.26	±0.12	±0.10	±0.19	±0.04	±0.26	±0.08	±0.11	±0.47

Figure 13: EDX (Energy Dispersive X-ray) analysis of the control sample .

From Figures 12 and 13, it can be seen that the chemical composition has practically not changed; however, the proposed sample (Figure 5) exhibits a more porous structure, which will lead to additional thermal insulation and a reduction in the material cost.

4 CONCLUSIONS AND RESULTS

1. The existing technology requires more manual labor compared to the proposed one, such as the installation of connections, placement of polystyrene plates, and sealing joints between polystyrene plates.

2. The proposed technology will reduce the production time of each panel by 20 minutes, increasing the productivity of the technological line and reducing the labor intensity of the product manufacturing process.

3. The layer of thermal insulation polystyrene concrete is non-flammable, whereas the polystyrene plate is a combustible material.

4. The air-entraining additive, in combination with steam curing, allows increasing the porosity up to 4.5% without reducing strength.

5. Experimental studies in laboratory conditions have shown that the plasticizer can reduce the amount of mixing water by more than 10%.

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