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Foamed Geopolymers as Low--Emission Insulating Materials with CO_2 Sorption Capability – Porosity, Thermal Conductivity, and Adsorption Performance

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Abstract

The article presents the results of research on foamed geopolymer materials as potentially dual-function building materials, combining thermal insulation properties with the ability to physically adsorb carbon dioxide. The materials were developed on the basis of fly ash, using hydrogen peroxide as a foaming agent. Two variants of the foaming agent quantity were used to assess how this quantity affects the type of porosity, thermal insulation, and CO_2 adsorption capacity. The porous structure was characterised using mercury porosimetry and physical CO_2 adsorption. A full analysis of their insulating and accumulating properties was also carried out. Measurements of the thermal conductivity coefficient (λ) showed that these materials have low thermal conductivity (in the range of 0.101 W/m·K), which confirms their suitability as ecological building insulators. At the same time, sorption tests performed using a physical sorption analyser confirmed the ability of selected composites to adsorb CO_2, with a noticeable influence of porosity parameters depending on the amount of blowing agent used on the efficiency of the process. An unexpected result of the research was the conclusion that a smaller amount of foaming agent may be more beneficial in terms of CO_2 adsorption capacity, while maintaining similar insulation parameters. The results suggest that properly designed foamed geopolymers can serve a dual function – as insulation materials and passive CO_2 adsorbents, thus supporting efforts towards sustainable development and decarbonisation of construction. The results obtained provide a basis for further in-depth analyses related to the possibility of using foamed geopolymers as carbon dioxide-absorbing materials.

Keywords: geopolymer foams, insulation materials, porous materials, dual-purpose building materials, CO_2 adsorbents

1. Introduction

Geopolymers are materials belonging to the group of inorganic polymers, which are amorphous aluminosilicate materials synthesized in strongly alkaline environments at temperatures not exceeding 100°C (Ghafoor, 2025). They have been known for at least several decades, but their intensive development took place at the beginning of the 21st century. Currently, thanks to their unique properties, geopolymer materials are attracting increasing interest from both the scientific community and entrepreneurs operating in the construction industry (Chen, 2025). However, despite the continuous development of these materials, there are still many barriers to their implementation. Some scientists believe that they are an alternative to traditional concrete only in selected advanced/niche applications. Therefore, geopolymers are often seen only as an academic curiosity with implementation potential in niche areas (Feng, 2025). They are characterized by greater compressive strength than traditional concretes based on conventional Portland cement, and also have very high resistance to high temperatures, up to 1000°C, and resistance to most aggressive corrosive environments (Iong, 2025). In addition, their environmental impact during the manufacturing process is potentially less harmful than that of Portland cement (Elgarahy, 2023). The use of geopolymer binders in environmental protection and the immobilization of hazardous substances is extremely interesting and beneficial. Their high resistance to environmental conditions allows them to be used, for example, in securing landfills, where they can form an impermeable layer preventing waste from coming into contact with the environment. They are also able to immobilize heavy metals more effectively than traditional concretes. Therefore, they are a potential material for the disposal of various groups of waste (Tian, 2021). Due to stricter environmental regulations and the search for new alternative insulation materials, foamed geopolymer materials have been gaining importance for some time (Przybek, 2024; Bąk, 2023). Although they do not achieve the thermal conductivity parameters of standard insulation materials, their excellent thermal resistance to temperatures exceeding even 1000˚C makes them fire-safe materials (Przybek, 2024; Marczyk, 2025). I addition, it turns out that these materials can simultaneously absorb/store CO_2 (Freire, 2025).

The phenomenon of carbon dioxide (CO_2) adsorption on porous materials is attracting increasing interest due to the need to reduce greenhouse gas emissions. Among the analyzed adsorbents, particular attention is paid to synthetic zeolites (especially types 13X, 4A, 5A) and geopolymers, as well as composites combining both types of materials.

Zeolites, thanks to their high proportion of microscopic pores and appropriately matched skeleton structure, exhibit very high adsorption capacities for CO_2, reaching values of even above 3.9 mmol·g^{-1} under conditions of up to 1.6 bar and a temperature of 25–35°C. The best adsorption parameters are exhibited by 13X and 4A zeolites, which results from their appropriate pore size and electrostatic nature (Khoramzadeh, 2019; Harper, 2021).

Geopolymers, as inorganic materials chemically cured at low temperatures, are an environmentally friendly alternative to traditional sorbents. Their specific surface area and porous structure can be modified by the addition of foaming agents or mineral additives. The adsorption capacity of pure geopolymers for CO_2 is usually in the range of 0.2–0.3 mmol·g^{-1}, which is lower than that of zeolites, but sufficient for auxiliary applications or in hybrid systems (Minelli, 2018).

In order to improve the sorption properties of geopolymers, geopolymer--zeolite composites have been developed, which allow the stiffness and mouldability of the geopolymer matrix to be maintained while introducing active zeolite micropores. An example is the study by Papa et al., in which composites with CO_2 adsorption of 2.6 mmol·g^{-1} were obtained for the Na-G1.2-4A-1 system at a pressure of 1 atm and a temperature of 35°C, which is comparable to pure zeolite 13X (Papa, 2023).

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It is worth noting that the type of geopolymer matrix used (Na^+ vs K^+) significantly affects the ability to synthesize zeolites in situ in the material structure. Sodium matrices favour the formation of NaA-type zeolite, while the presence of potassium can disrupt this process through competitive ion exchange phenomena (Zhou, 2023; Kumar, 2020).

In turn, research by Schneider and colleagues has shown that geopolymer--zeolite 13X composites, obtained from waste materials, can achieve adsorption capacity similar to that of pure zeolites, while maintaining high mechanical resistance and thermal stability (Schneider, 2025; Schneider, 2025).

This article presents the results of innovative research on the relationship between the adsorption capacity of geopolymer foams and their insulating properties depending on the amount of porogen. The results of porosity and CO_2 sorption capacity tests are presented. The presented results prove that increasing the amount of foaming agents does not necessarily lead to an increase in porosity and improvement in thermal insulation properties, and may reduce the CO_2 adsorption capacity.

2. Materials and methods

Fly ash from the Skawina combined heat and power plant was used as the base material for the production of foamed geopolymers. The oxide composition of the main geopolymerization precursor (ash) is presented in Table 1 below. The oxide composition was determined using X-ray fluorescence (XRF) analysis with a SHIMADZU EDX-7200 spectrometer (SHIMADZU Europa GmbH, Duisburg, Germany).

Table 1. Oxide composition of fly ash used in the tests

Precursor	Oxide Composition (wt. %)						
	SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	Ti_02	SO_3
Fly ash	59.27	30.35	3.68	2.24	2.57	0.66	0.33

The foamed geopolymer compositions also contained components such as sand, ash microspheres, cement, surfactant, as well as a porogen and an alkaline solution (activator). The sand used as a filler is fine-grained quartz sand from the Świętochłowice Sand Pit (Świętochłowice, Poland). High-alumina cement with the trade name Górkal 70 (manufactured by Górka Cement Sp. z o.o., Trzebinia) – a hydraulic additive – was introduced as a stabilizer of the foamed porous structure. The ash microspheres used (TERMO-REX S.A., Jaworzno) served as a lightweight filler to increase the thermal insulation properties of the material. In order to stabilize the porous structure, improve the uniformity of pore distribution, change the surface tension of the mixture, and facilitate the formation of pores, a surfactant – syringaldehyde, supplied by Merck (Merck, Germany), was also added to the mixture. The use of Syringaldehyde as a surfactant and its positive effect on the foaming process have been demonstrated in previous studies by the authors (Marczyk, 2025; Łach, 2021). Syringaldehyde (4-hydroxy-3,5-dimethoxybenzaldehyde) acts mainly as a surfactant and pore stabilizer in geopolymer foams. The porogen was 35% hydrogen peroxide. The alkaline solution was prepared as a mixture of 10M aqueous NaOH solution (PCC Rokita SA, Brzeg Dolny, Poland) and sodium water glass (an aqueous solution of sodium silicate R-145 with a molar ratio of SiO_2/Na_2O of 2.5 and a density of approximately 1.45 g/cm^3, supplied by Zakłady Chemiczne ANSER (Wiskitki, Poland). Both components (NaOH solution and water glass) were used in a mass ratio of 1:2.5 (NaOH: water glass).

A GEOLAB M/LMB-s laboratory mixer (Warsaw, Poland) was used to produce geopolymer foams. In the first stage of producing porous geopolymers, loose

components such as fly ash, sand, microspheres, cement, and surfactant were mixed. The mixture was stirred for 5 minutes at a constant speed of 50 rpm to achieve initial homogenization of the material and even distribution of the components throughout the mixture. The next step was to introduce an activating component into the liquid system – a previously prepared alkaline solution. After introducing the alkaline solution into the dry mixture, the mixing process was continued for another 10 minutes. During this time, a homogeneous, plastic mass with appropriate rheological properties was obtained, enabling further foaming. In order to obtain a porous structure, 35% hydrogen peroxide was added to the previously prepared mixture as a foaming agent. Two variants were made to the amount of foaming agent used. After adding the appropriate amounts, the whole mixture was stirred for another 2 minutes, which allowed for the even distribution of the foaming agent and the start of the foaming reaction. The liquid mass prepared in this way was immediately transferred (poured) into the previously prepared moulds, which were secured with sealing foil. The samples were placed in an SLW 750 chamber dryer (POL-EKO Perfect-Environment, Wodzisław Śląski, Poland), where they were heated at 75°C for 24 hours. This stage was crucial for the geopolymerisation process and for ensuring a stable material structure. After annealing, the samples were demoulded and left to cure under laboratory conditions (room temperature, relative humidity approx. 50%) for 28 days. After the curing period, the samples were cut to the appropriate sizes – 20 × 20 × 3 cm. Table 2 presents detailed specifications of the tested samples along with their quantitative composition. Figure 1 shows the appearance of sample specimens produced for testing, immediately after demoulding and after cutting them to the appropriate sizes required for testing their thermal insulation properties.

Table 2. Markings of samples produced for testing, together with the quantitative composition of individual components (own elaboration)

Sample ID	Sand weight [wt. %]	Microsphere weight [wt. %]	Fly ash weight [wt. %]	Cement weight [wt. %]	Syringaldehyde stabilizer weight [wt. %]	Amount of foaming agent – 35% H_2O_2 [wt. %]	Amount of alkaline solution [wt.%]	H_2O_2 / fly ash [w/w]	Activator/ fly ash [w/w]
GeoFOAM25	7	14	70	9	0.005	0.025	0.35	0.000357	0.00500
GeoFOAM75	7	14	70	9	0.005	0.075	0.35	0.001071	0.00500

The compositions presented in Table 2 differed only in the amount of foaming agent. Two variants were prepared in the form of samples with the addition of 25 ml of H_2O_2 and 75 ml of H_2O_2. The choice of these variants was dictated by the main objective of the study, which was to check how the amount of foaming agent affects density, thermal conductivity, and CO_2 adsorption capacity.

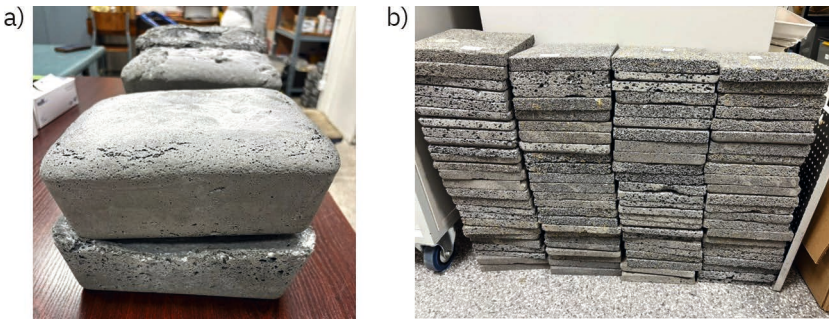

Fig. 1. Foamed geopolymers after demoulding (a) and slabs cut to size for testing insulation properties (b) (photo by Michał Łach)

The thermal properties of the tested geopolymer foam compositions were measured using a Netzsch (Selb, Germany) HFM 446 Lambda plate apparatus. This device meets the requirements of a number of international standards, such as ASTM C1784 (ASTM, 2020), ASTM C518 (ASTM, 2021), ISO 8301 (ISO, 1991), EN 12664 (EN, 2021), and other recognized standards. Thermal

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conductivity and thermal resistance tests were carried out in the range of 0–20°C, which corresponds to the actual operating conditions for insulation materials used in construction. As part of the same test procedure, the HFM 446 apparatus was also used to measure the specific heat (Cp) at 27.5–32.5°C and the volume density of the samples. This allowed for a more complete characterization of the insulation and accumulation properties of the materials, which is important when assessing their potential use in insulation systems. The mass of the samples was determined with high accuracy using a RADWAG PS 200/2000.R2 analytical laboratory balance (Radom, Poland) with an accuracy of 0.01 g, and the geometric dimensions were determined using a precision caliper with a resolution of 0.01 mm. Based on the collected data, the thermal conductivity coefficient (λ), thermal resistance (R), specific heat (Cp), and density were calculated, which enabled a comprehensive assessment of the materials in terms of their functionality as modern, low-emission thermal insulators.

The specific surface area and CO_2 adsorption capacity were measured using an Autosorb iQ automatic gas sorption analyzer (Anton Paar GmbH, Graz, Austria), equipped with ASiQwin v5.21 software. The following measurement parameters were used: Sorption gas: carbon dioxide (CO_2); Cryogenic bath temperature: 273.15 K (0°C, ice bath); Reference pressure (Po): 1 atm.; Measuring cell diameter: 9 mm (without rod). The samples were subjected to vacuum degassing at 350°C for approximately 9 hours to remove moisture and volatile impurities.

Figure 2 shows the test setup for CO_2 adsorption in foamed geopolymer structures.

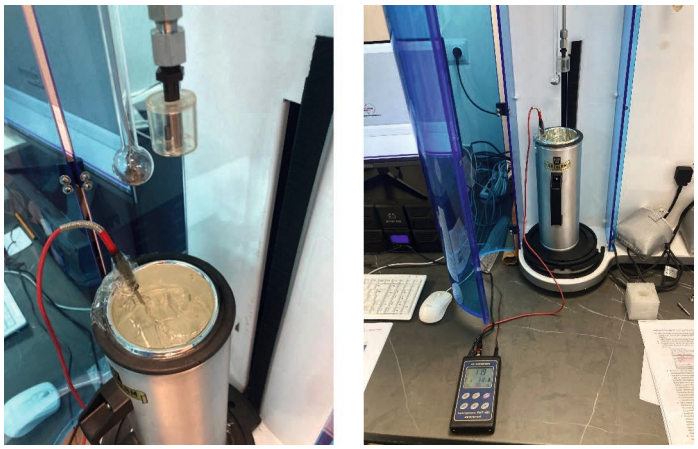

Fig. 2. Station for testing CO_2 sorption in foamed geopolymer structures (a tank with liquid cooled to 0°C in which the test sample is immersed during measurement) (photo by Michał Łach)

The pore size distribution, total pore volume, and specific surface area were determined using mercury porosimetry with a PoreMaster 33 device (Anton Paar GmbH, Graz, Austria). To cover the full range of pore sizes, the tests were conducted in two pressure ranges – low and high – using separate measuring chambers.

3. Results and discussion

The thermal insulation, accumulation, and density properties of the samples produced in two variants (different amounts of H_2O_2) and cut to the appropriate sizes were tested. The results of the tests are presented in Table 3 below.

Both samples exhibit similar specific heat values (1.51–1.52 kJ/kg·K), suggesting that an increase in the amount of H_2O_2 does not significantly affect the heat storage capacity per unit mass. Despite the use of three times more foaming agent, the GeoFOAM75 sample has a higher density (453 vs 397 kg/m^3), which may seem surprising, but it is likely that during foaming, the higher

amount of H_2O_2 caused a more violent reaction, and the pores may have collapsed. The use of a larger amount of H_2O_2 (75 ml) leads to a slight decrease in thermal conductivity from 0.10636 to 0.10104 W/m·K, but the difference in the λ parameter is only about 5%, which indicates that the potential for further reducing thermal conductivity by increasing the amount of H_2O_2 is not a good direction. Based on the results presented in Table 3, it can be concluded that increasing the amount of foaming agent does not bring proportional benefits in terms of thermal insulation and, what is more, may lead to an increase in density, i.e., the opposite effect to that expected is achieved. In terms of thermal properties, the addition of smaller amounts of H_2O_2 seems optimal, as it provides good thermal conductivity reduction, lower density (advantageous for use as a lightweight building material or thermal insulator), comparable thermal parameters with lower chemical consumption, and a lower risk of losing the stability of the foamed structure.

Table 3. Results of tests for thermal conductivity, thermal resistance, specific heat, and density (own elaboration)

Sample ID	Average thermal conductivity at 0–20°C [W/m·K]	Average thermal resistance [m²·K/W]	Average specific heat at 27.5–32.5°C [kJ/kg·K]	Average density [kg/m³]
GeoFOAM25	0.10636	0.2418	1.511	396.959
GeoFOAM75	0.10104	0.1852	1.517	453.406

Below is a graphical summary of the results from a mercury porosimeter for two series of foamed geopolymers, differing in the amount of foaming agent used (H_2O_2 – 25 ml vs 75 ml). For each series, average values were calculated, and data from the low and high pressure ranges were combined.

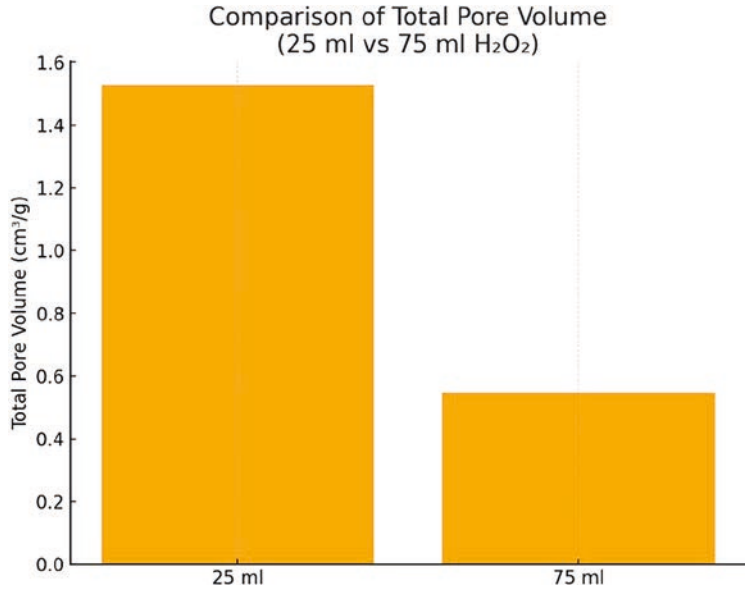

Fig. 3. Comparison of the total pore volume in materials produced with varying amounts of pore-forming agents

Tests conducted on a mercury porosimeter showed that the total pore volume for individual samples was as follows: GeoFOAM 25 ml: 1.53 cm^3/g; GeoFOAM 75 ml: 0.55 cm^3/g, while the specific surface area was: GeoFOAM 25 ml: 35.9 m^2/g; GeoFOAM 75 ml: 23.6 m^2/g. It should be noted here that this is the specific surface area determined using a mercury porosimeter, and the values obtained in this test will differ from the BET surface area, which is determined by testing on a physical sorption analyzer.

Based on data obtained from a mercury porosimeter and sample density measurements, it is possible to estimate the bulk porosity of the tested material. Although porosity has not been determined directly, it can be approximated using the total pore volume measured by the mercury method and the sample

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density converted to g/cm³. Mass porosity is defined as the ratio of the total pore volume to the sum of this pore volume and the volume corresponding to the mass of the sample at its density. In other words, porosity reflects the fraction of the total volume of the sample occupied by pores in relation to the total volume of the material, including both pores and the volume of the material itself. The presented method allows for a quick and reliable estimation of the porosity of a material in the absence of direct measurements, based solely on experimental data.

Table 4. Estimation of the bulk porosity of a material based on pore volume and sample density (own elaboration)

Sample ID	Average density [g/cm³]	V_sample [cm³/g]	Pore volume [cm³/g]	Porosity [%]
GeoFOAM25	0.396959	2.519	1.53	61
GeoFOAM75	0.453406	2.205	0.55	25

The differences in thermal conductivity between GeoFOAM25 and GeoFOAM75 materials are primarily due to different microstructural parameters rather than directly related to their bulk density. Analysis of mercury porosimetry data indicates that GeoFOAM25 is characterized by a high total pore volume, corresponding to a porosity of ~61%, and a larger specific surface area (35.9 m²/g). These parameters indicate the presence of numerous small pores connected by thin partitions, which increases the proportion of heat conduction through the solid phase and promotes the intensification of heat transport through the gas phase. As a result, this leads to an increased effective thermal conductivity of approximately 0.106 W/(m·K). In contrast, GeoFOAM75 has a significantly lower total porosity (~25%) and a smaller specific surface area (23.6 m²/g), indicating a more compact microstructure with thicker cell partitions and a higher proportion of closed gas pores. This architecture limits the number of continuous heat conduction paths in the solid phase and reduces effective heat transport in the gas phase, resulting in a lower thermal conductivity of 0.101 W/(m·K). This seemingly unusual relationship–higher density with lower thermal conductivity–results from qualitative differences in pore geometry, their connectivity, and the nature of the cell partition, rather than from the simple proportion of the solid phase in the material.

Figure 4 shows a comparison of the pore volumes for both series of tested samples, divided into micro-, meso-, and macropores.

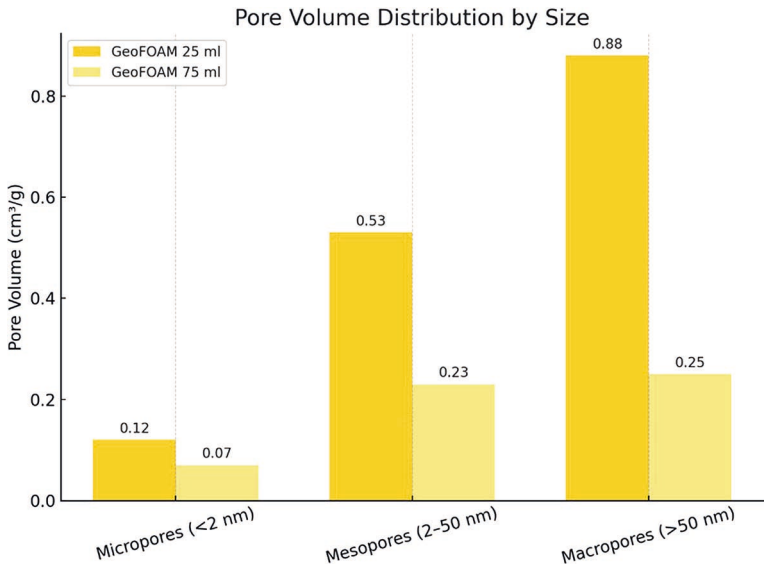

Fig. 4. Comparison of histograms showing pore volumes divided into micro-, meso-, and macropores for both series of foamed geopolymers (GeoFOAM 25 ml vs GeoFOAM 75 ml)

Table 5 presents a comparison of the percentage of individual types of pores for both series of tested samples.

Table 5. Comparison of the percentage of individual types of pores for both series of tested samples (own elaboration)

Sample ID	Micropores (<2 nm)	Mesopores (2–50 nm)	Macropores (>50 nm)
GeoFOAM25	7.8%	34.6%	57.5%
GeoFOAM75	12.7%	41.6%	45.6%

The results obtained show that samples with lower H_2O_2 concentrations have almost three times greater pore volume, which may indicate more effective and stable foaming. The efficiency of the foaming process may be higher at lower H_2O_2 concentrations, probably due to more stable foam formation and better pore binding by the geopolymer matrix. In addition, with a larger amount of foaming agent, significantly more micropores and fewer macropores are formed, which may affect, among other things, the ability to effectively adsorb CO_2.

Figure 5 below shows the CO_2 sorption capacity results for 25 ml and 75 ml GeoFOAM samples. Based on the data measured on the physical sorption analyzer, the actual CO_2 sorption capacity for the foamed geopolymer samples was calculated. The sorption capacity values for the individual variants were as follows:

- GeoFOAM 25 ml: 0.0419 mmol/g
- GeoFOAM 75 ml: 0.0303 mmol/g

The measurements were carried out solely to compare the results obtained in order to determine whether a larger amount of foaming agent contributes to an increase in porosity, specific surface area, and CO_2 adsorption capacity. The parameters obtained are significantly lower than those reported in the literature for foamed geopolymer and zeolite composites. It should be emphasised that when comparing the results, it is necessary to take into account the measurement parameters. The authors of this paper conducted experiments at 0°C, and the results cannot be compared with the literature measurements conducted at 35°C.

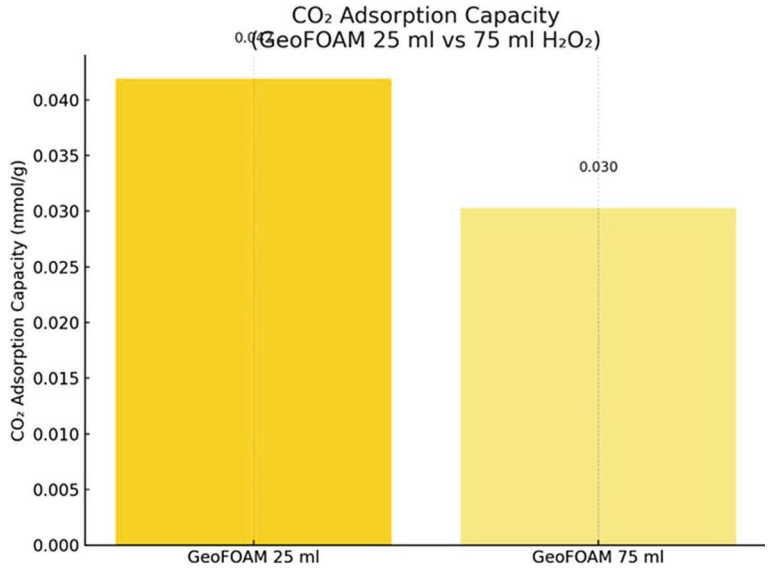

Fig. 5. Comparison of sorption capacities for foamed geopolymers, for variants with the addition of 25 ml H2O2 and 75 ml H_2O_2

The results obtained allow us to conclude that the variant with three times less foaming agent (25 ml H_2O_2) shows approx 38% higher CO_2 sorption capacity compared to the 75 ml sample. This is related to the larger total pore volume, as the variant with three times less foaming agent has almost three times the total pore volume.

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4. Summary and conclusion

The study aimed to determine the effect of the amount of foaming agent on the structure (porosity distribution) of geopolymer foams. Two variants of the foaming agent, H_2O_2, were used. The effect of the foaming agent was linked to its ability to adsorb CO_2. The results obtained are the basis for further in-depth analysis of this issue. As a result of the research, the following conclusions could be drawn:

- The foaming process of geopolymers is difficult to control, and there are often problems with the repeatability of obtaining the desired structures. A larger amount of foaming agent does not always translate into better insulation parameters.
- The insulating properties remained comparable, or even slightly better, for GeoFOAM75, despite three times the porogen content, which suggests that increasing it was ineffective.
- The CO_2 adsorption capacity was higher in the series of samples with less foaming agent, which was since the total pore volume was significantly higher for the GeoFOAM 25 sample.
- Foamed geopolymer materials can not only act as thermal insulators, but their use as CO_2 adsorption materials can also be considered. However, their adsorption capacities are not very high, so zeolite structures should be produced simultaneously during their manufacture.
- Further detailed research is needed to develop a special model that allows the prediction of the possibility of obtaining an optimal structure depending on the parameters influencing the foaming process (including the amount of blowing agents). At this stage, it is difficult to determine the application potential of CO_2 adsorption systems.

Some of the graphs and graphical summaries (Figures 3, 4, and 5) of the results were developed using artificial intelligence-based tools, including OpenAI's ChatGPT (GPT-4o) model. In addition, sections of text in Chapter 3 were pre-formatted and linguistically optimized using the same model to improve readability and editorial consistency. All content was then verified and approved by the authors. The AI model was used solely to improve the readability of the paper.

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