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OWN CONTRIBUTIONS FOR PRODUCING POROUS BUILDING MATERIALS UNDER ECONOMIC AND ENVIRONMENTALLY FRIENDLY CONDITIONS: A REVIEW

BY

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Abstract. The paper reviews the main modern techniques for producing porous building materials exhibited in the literature and the contribution of the Romanian authors’ team of the current paper to their experimental development. The review refers to important methods applied in recent decades in the world that have greatly influenced the adoption of more cost-effective and much more environmentally friendly procedures. Innovative techniques were applied in cellular glass production by high temperature sintering-foaming, the most important being microwave use for high-energy efficient heating processes. Also, other technological improvements were tested. Cold preparing cellular glass by using aluminum powder as pore-providing agent and $\text{Ca}(\text{OH})_2$ activating solution were successfully applied especially in energy terms. Recent innovative method

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of producing geopolymer concrete from alumina-silicate waste was also in authors' research attention. Other innovative techniques such as CO₂ capture/storage in concrete, "one-part" mixing in concrete making, and converting inert waste into pozzolanic glass were tested with authors' contributions.

Keywords: cellular glass, microwave heating, cold preparing, geopolymer concrete, CO₂ capture.

1. Introduction

Since the last decades of the 20th century and continuing also in present, humanity's concern for reducing energy consumption specific to energy-intensive industrial processes and for reducing the CO₂ footprint has progressively grown. Implications on the reduction of natural sources of traditional fossil fuels and the potentially serious effects on the planet's climate change constitute major warning signals, especially for the future (Lindsey and Dahlman, 2025). Consequently, in addition to important international decisions to reduce or even stop some common technologies that consume large amounts of primary energy (EEA agency, 2025), such as the cement industry and others, special effervescence in the field of large-scale research has been exhibited on achieving, under economic and environmentally friendly conditions, of new materials and products, with newly created value, as an alternative to those that have become unacceptable in the current crisis situation (such as: geopolymer, hempcrete, various materials using industrial by-products like fly ash, silica fume, metallurgical slag, bio-based materials, alkali-activated binders as well as innovative carbon-negative materials) (Althoey *et al.*, 2023).

2. Methods, Materials, and Results

World research in porous building material manufacturing under cost-effective and ecological conditions has intensively developed, including also authors of the current study.

First, research has been conducted on preparing cellular glass as a thermal insulation material, under conditions of remarkable energy efficiency, obtained by applying electromagnetic waves (microwaves) in the high-temperature sintering process of recycled waste glass.

In energy terms, industrial manufacturing using conventional heating methods of one kilogram of new glass requires about 4500 kJ, i.e. 1.25 kWh, while producing the same glass amount from recycled waste requires only about 500 kJ, i.e. 0.139 kWh (Energocell, 2014). Microwave sintering-foaming is an efficient and promising method for recycling glass waste into lightweight, porous foam materials. This process involves heating glass waste in a microwave oven, causing it to melt, foam, and solidify into a cellular structure. Microwave heating offers advantages compared to conventional methods, including faster processing

times, reduced energy consumption, and potentially improved product properties. Although known for over 80 years, the method of heating solids at high temperatures is still not industrially applied, with only drying and heating processes at low temperatures being preferred (Kharissova *et al.*, 2010).

Experimental results obtained in manufacturing process of cellular glass using indirect microwave heating are presented in (Paunescu *et al.*, 2022a). The intensification of microwave absorption was achieved using a silicon carbide crucible with the wall covered with yttrium oxide (Y_2O_3) film. Y_2O_3 is a versatile material with numerous applications, including its use as a dielectric layer, corrosion-resistant coating, and phosphor material. It is known for its high melting point, chemical inertness, and adjustable dielectric properties. Microwave heating and the use of yttrium oxide film represent the originality of the paper. The recipe containing glass waste, coal fly ash and silicon carbide allowed making cellular glass at 960-970°C with economical energy consumption (under $0.86 \text{ kWh}\cdot\text{kg}^{-1}$). The products have typical features of cellular glass with density in the range of $0.27\text{-}0.33 \text{ g}\cdot\text{cm}^{-3}$, heat conductivity within the limits of $0.064 - 0.073 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ and compressive strength between 1.35-1.45 MPa. Images of cellular glass products achieved by the method mentioned above are exposed in Fig. 1.

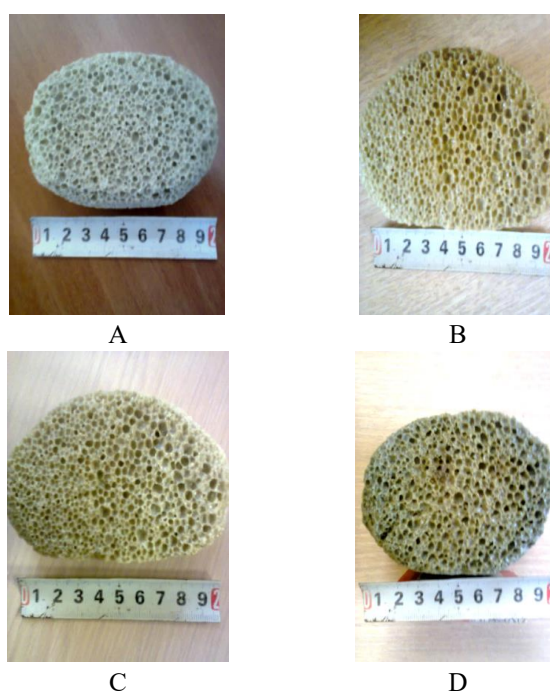


Fig. 1 – Images of porous samples made through microwave heating
A – sintered at 960°C; B – sintered at 965°C; C – sintered at 967°C;
D – sintered at 970°C.

Another microwave-assisted method of making cellular glass-ceramic is shown in (Paunescu and Axinte, 2022b). Residual glass, fly ash, silicon carbide (SiC), and kaolin were mixed to be sintered at high temperatures within the limits of 950-975°C. The heating technique procedure was original, adopting the own method of predominantly direct microwave heating. The thermal insulation characteristics of the froth were excellent (apparent density between 0.22-0.28 g·cm⁻³, porosity in the range of 86.7-89.5%, and thermal conductivity between 0.055-0.065 W·m⁻¹·K⁻¹), while compressive strength had relatively low values, but satisfactory for this type of porous material (1.8-2.5 MPa). Water uptake had low values below 1.2 vol. % and the pore size was under 1 mm. The specific energy consumption was very low (between 0.75-0.83 kWh·kg⁻¹), being influenced by applying the electromagnetic wave effect. The surface appearance of the optimal cellular glass-ceramic sample (A) and its internal structure in microstructural terms (B) are shown in Fig. 2.

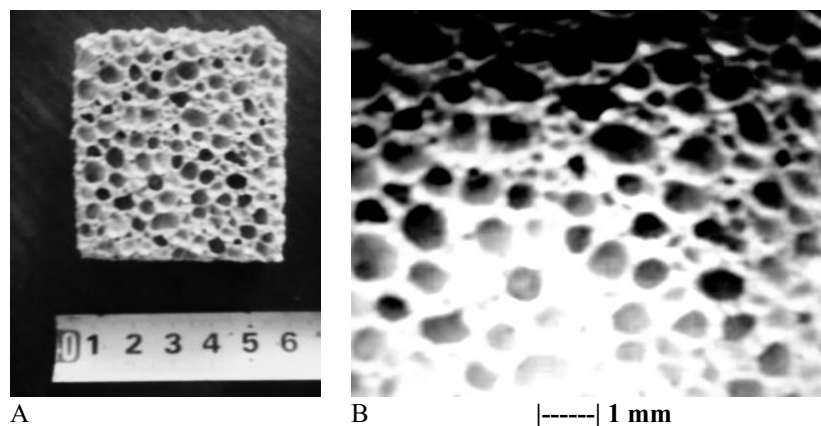


Fig. 2 – Optimal cellular glass-ceramic sample made by microwave-assisted method
A – surface appearance; B – microstructural aspect.

A cellular glass with excellent thermal insulation properties (density of 0.38 g·cm⁻³, porosity of 81.9%, and heat conductivity of 0.089 W·m⁻¹·K⁻¹), high compressive strength of 3.9 MPa, and acceptable microstructural homogeneity with pore size in the range of 0.6-1.0 mm was obtained by sintering at 927°C of waste flat glass, a residual glass type that is not usually used in the cellular glass manufacturing process. The peculiarity of manufacturing recipe is the combined use of two microwave-susceptible foaming agents (silicon carbide and silicon nitride). Also, coal fly ash and MnO₂ as an oxygen-providing agent were added to the starting mixture (Ioana *et al.*, 2022). The combined use of the two foaming agents and applying predominantly direct microwave heating technique were original elements of this work compared to the known methods presented in the

literature. The heating rate reached high values ($22.5\text{--}26.5^\circ\text{C}\cdot\text{min}$) and implicitly, the specific energy consumption was low ($0.77\text{--}0.92\text{ kWh}\cdot\text{kg}^{-1}$).

The physical appearance of the optimal cellular glass specimen is exhibited in Fig. 3A and its microstructural appearance is shown in Fig. 3B.

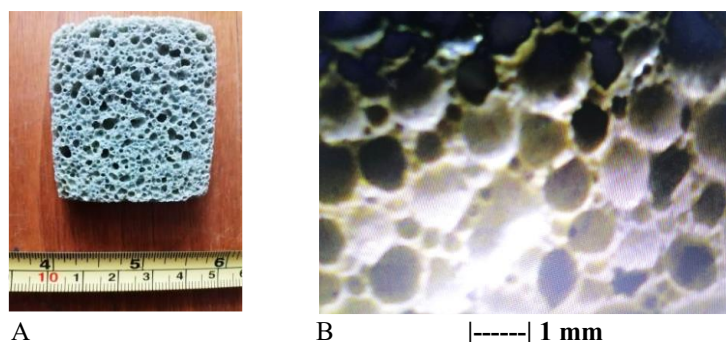


Fig. 3 – Physical and microstructural appearance of cellular glass
A – physical appearance; B – microstructural appearance.

An optimal cellular glass specimen with excellent thermal insulation properties including low density ($0.26\text{ g}\cdot\text{cm}^{-3}$), very low thermal conductivity ($0.064\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$), and high porosity (87.6%) as well as, at the same time, significantly higher compressive strength (6.0 MPa) was experimentally made (Paunescu *et al.*, 2023a). The starting mixture was composed of finely ground solid materials (residual glass, borax, and sodium carbonate) and liquids (sodium silicate solution and added water), separately processed and then mixed together. The resulting dense paste was poured into a mould, pressed, removed from the mould, and freely loaded into the microwave oven. The sintering process of the optimal sample was carried out at 825°C , the foamed material resulting as a cellular product adequate for use as an insulating material in construction under conditions of mechanical stress. Images of the optimal cellular glass sample are exhibited in Fig. 4A and B.

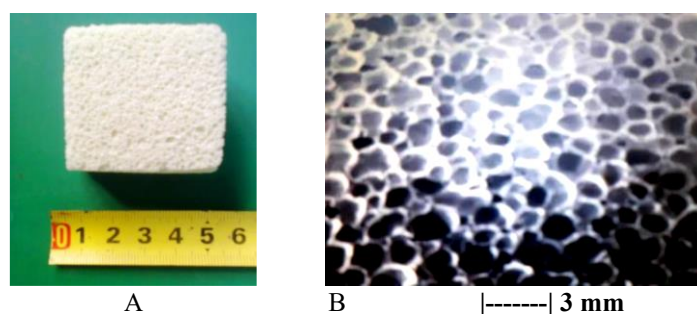


Fig. 4 – Physical aspect and microstructural peculiarities of optimal cellular glass specimen
A – physical aspect; B – microstructural peculiarities.

An important evolution in terms of energy efficiency of cellular glass preparation processes was the cold foaming of the raw material, process also approached by the Romanian research team (Paunescu *et al.*, 2021). Recently, several techniques for preparing porous concrete have been applied at ambient temperature. For this purpose, synthetic foaming agents have been selected. (Kaneshira *et al.*, 2013) designed a method based on the use of hydrogen gas as a foaming agent released from the corrosion of fine aluminum powder in an aqueous calcium hydroxide solution. The aluminum oxide (Al_2O_3) existing in an extremely thin layer on the aluminum particle surface generates aluminum hydroxide, which reacts with Ca^{2+} ions in the alkaline solution to form hydrogen at ambient temperature. The slurry formed by mixing the powder with water represents an adequate environment for the formation of hydrogen bubbles, subsequently generating the solidified porous matrix. Using colourless and green waste glass, aluminum powder with grain size under $15\ \mu\text{m}$, $\text{Ca}(\text{OH})_2$ aqueous solution (1:6 concentration), and carboxymethyl cellulose as a foam stabilizer, the Romanian team made cellular glass samples with apparent density between $0.25\text{-}0.34\ \text{g}\cdot\text{cm}^{-3}$, thermal conductivity in the range of $0.059\text{-}0.079\ \text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, and compressive strength within the limits of $2.4\text{-}2.6\ \text{MPa}$. The optimal sample (see Fig. 5A, B) had following values: density of $0.31\ \text{g}\cdot\text{cm}^{-3}$, heat conductivity of $0.070\ \text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, and compressive strength of $2.5\ \text{MPa}$.

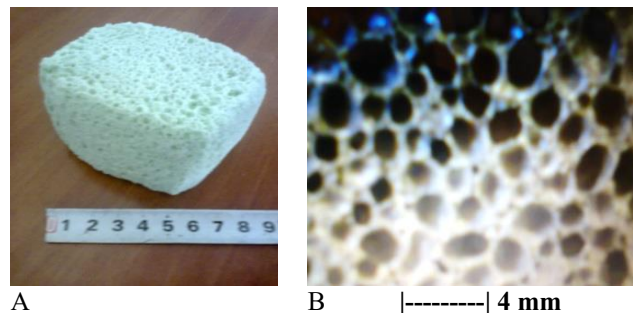


Fig. 5 – Optimal sample aspect and microstructural appearance of the cold preparing cellular glass

A – sample aspect; B – microstructural appearance.

Another modern method of manufacturing construction materials focuses on the use of industrial by-products or natural alumina-silicate materials, activated by their reaction with an alkaline liquid solution based on sodium/potassium hydroxide and sodium/potassium silicate. The product thus obtained, called geopolymer, has remarkable physical, mechanical, chemical and other fire, water or frost resistance abilities, superior to construction materials made so far, representing a sustainable alternative to Portland cement (Chen *et al.*, 2022). Geopolymer, as a new type of inorganic cementitious material, was created by the French researcher J. Davidovits at the end of the 20th century

(Davidovits, 1991) and represents an important innovative concept, currently developed by several specialist teams around the world. Geopolymerization is a chemical process that facilitates the formation of a resistant and durable material with a three-dimensional polymeric structure (Siyal *et al.*, 2024). Designing and testing the cellular geopolymers was one of the main concerns of the Romanian research team. Such a geopolymer based on fly ash and metakaolin was developed in the work (Paunescu *et al.*, 2023b). The traditionally used foaming agent (hydrogen peroxide) was replaced by sodium perborate, which is easier to handle and more stable. In order to increase the geopolymer strength, bentonite clay as a nano-material was added to the mix. The new product density had a low value ($470 \text{ kg}\cdot\text{m}^{-3}$) and also thermal conductivity was low ($0.104 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$), while compressive strength reached a relatively high value (7.5 MPa). Images of the surface appearance of the optimal specimen and its microstructural appearance are exhibited in Fig. 6A, B.

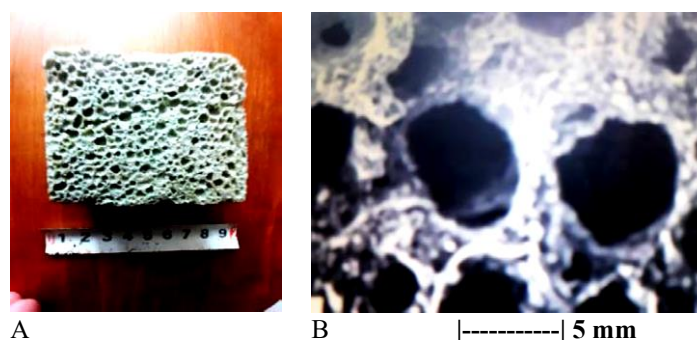


Fig. 6 – Optimal specimen appearance and microstructural aspect of the geopolymer

A – optimal specimen appearance; B – microstructural appearance.

The retrospective analysis of results obtained by the team of Romanian authors in the field of producing porous materials, with thermal insulation properties for buildings, can lead to the conclusion of more or less major contributions to the development of this industrial field. The results were obtained under small-scale experimental conditions, but they were promising, especially the reduction of energy consumption of thermal sintering processes by applying electromagnetic waves.

3. New Geopolymer Research Trends and Authors' Contribution

Other recent research trends exhibited in the world literature regarding CO_2 capture and storage in concrete, adoption of "one-part" mixture geopolymer as well as the conversion of inert silicate waste (residual glass) into pozzolanic glass as a suitable replacer of Portland cement in concrete preparing have been

experimentally investigated by the authors of this paper. The results of the three investigations mentioned above have been included in works, that are in present in various publication stages.

In the last few years, research interest on CO₂ capture and storage in concrete as a result of premature carbonation of hydrated 2CaO·SiO₂ (i.e. C-S-H), under conditions that C-S-H is the main binding component of the traditional binder (Portland cement), has increased. The literature has noted several studies on CO₂ storage in concrete. According to (Liu *et al.*, 2022), C-S-H carbonation occurs in three steps: dissolution, diffusion and slow reaction. During the reaction, C-S-H completely decomposes and the mixture including micro-crystalline calcium carbonate and modified calcium in silica gel are the final products of the reaction.

In the paper recently submitted to Nonconventional Technologies Review for publication (Paunescu *et al.*, 2025a), mineral carbonation (also called CO₂ mineralization) is a capturing technique of CO₂ bonds for the formation of carbonates. Water-solubility of carbonates is very low and they are practically stable under normal pressure conditions. Thus, the conditions for the definitive CO₂ storage are met. Early-age CO₂ binding process has the capacity to sequester it by its mineralizing, while ensuring growing the early-strength of concrete.

An innovative mixture type, called “one-part”, for the production of geopolymer concrete is considered safer, easier to handle and very adapted for in-situ construction works. In “one-part” mixtures, only one dry mix and water are required. The dry mix is made including a solid alkaline activator and a solid alumina-silicate precursor. The concentrated alkaline solutions used in the “two-part” mixture method are considered dangerous and corrosive. In accordance to (Matakah *et al.*, 2017), after the water addition to the “one-part” geopolymer mix, the geopolymerization process to obtain the final geopolymer takes place in four stages: ion exchange, hydrolysis, network decomposition, and release of silicon and aluminum. Unlike the “two-part” mixture, the solid silica sources react more slowly. According to (Luukkonen *et al.*, 2018), the development of “one-part” alkaline-activated geopolymers as alternative binders constitutes an adequate technical solution for construction applications involving in-situ casting.

Recent work made by Romanian authors (Paunescu *et al.*, 2025b) aimed at producing “one-part” geopolymer composite material using coal fly ash and granulated blast furnace slag as alumina-silicate precursors, sodium carbonate as a solid alkali activator, and sodium lignosulphonate as a water-reducer superplasticizer, constituting a dry powder mixture, to which water was added in the second stage. The results of the current experiment exhibited satisfactory thermal insulation properties, the density and heat conductivity values being quite low as well as quite high levels of compressive and flexural strength, early-age strength values after only 7 curing days being high considering the final mechanical strength values at the end of the 28 curing days. The features of the

optimal variant of the final product showed heat conductivity of $0.167 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$, compressive strength of 25.6 MPa (after 7 days) and 35.9 MPa (after 28 days), flexural strength of 7 MPa (after 7 days) and 9.8 MPa (at the curing end). Pore size of the optimal geopolymer specimen was in the range of 40-75 μm .

One of recent fundamental discoveries with implications for the choice of adequate alternative materials is activating the pozzolanic properties of available inert wastes. Both natural alumina-silicate materials (metakaolin, volcanic ash, siliceous sedimentary rock, etc.) and industrial alumina-silicate by-products (coal fly ash, silica fume, metallurgical slag, residual glass, etc.) are not reactive. However, it has recently been found that by finely grinding them, pozzolanic properties close to those of Portland cement can be activated. Pozzolanic properties are the characteristics of certain materials that, although not cementitious themselves, still have the ability to react with calcium hydroxide $\text{Ca}(\text{OH})_2$ from lime in the presence of water, forming cementitious compounds, called pozzolans. These have the capacity to develop strength and durability of concrete, or other cement-based products (Yao *et al.*, 2020). In concordance with the literature (McCarthy and Dyer, 1998), pozzolan composition includes SiO_2 , or SiO_2 together with Al_2O_3 , which with a fine granulation have the ability to react with $\text{Ca}(\text{OH})_2$ under normal conditions of temperature and pressure. As a result of this reaction, C-S-H gel is formed. Additional materials with cementitious properties are often used in the mix for making concrete as partial replacers for cement. The usual cement-compounds symbolically noted C_3S representing $3\text{CaO} \cdot \text{SiO}_2$ and C_2S representing $2\text{CaO} \cdot \text{SiO}_2$ react with water (by hydration process) forming the C-S-H gel ($3\text{CaO} \cdot 2\text{SiO}_2 \cdot 3\text{H}_2\text{O}$) that gives the concrete strength and $\text{Ca}(\text{OH})_2$ as a by-product of the reaction. The water-soluble by-product is removed from the concrete, leading to growing the concrete porosity and simultaneously to strength decrease. During the pozzolanic reaction, supplementary cementitious materials react with $\text{Ca}(\text{OH})_2$ to form an additional C-S-H gel. Consequently, the total amount of required cement is reduced. Thus, CO_2 emissions during the making process are reduced, durability is grown due to lower permeability and higher resistance to chemicals attack.

Materials used by the Romanian team (Paunescu *et al.*, 2026) in the own experiment were: CEM I cement type, amber glass powder recycled from post-consumer drinking bottle, sand and granite gravel as fine and coarse aggregates, sodium lignosulfonate as a superplasticizer, and working-water. Reducing the cement consumption through its replacement with up to 36% amber glass powder, a significant growing of compressive strength was obtained, reaching to 49.8 MPa after 56 curing days. Also, the flexural strength increased, reaching to 11.4 MPa after the same maximum curing time.

4. Discussion

Several performance techniques in the field of porous building materials, characterized by low energy consumption and environmental friendliness, have been exhibited in the international literature. Considering that the economic and ecological objectives of these innovative techniques are valid for the entire actual research, the authors' team of the current paper has been permanently in contact with the technological performances in the mentioned field and has tried to find viable improvements through the own experiments carried out on a small-scale.

The most important method of enhancing the microwave heating process was the use of a SiC crucible coated with a thin layer of Y_2O_3 . The sintering-foaming process of the waste glass-fly ash-SiC mixture was an economical one, specific energy consumption being below $0.86 \text{ kWh} \cdot \text{kg}^{-1}$, despite the high temperature ($960\text{-}970^\circ\text{C}$) of the process. Also, the microwave-assisted method of making cellular glass-ceramic according to the own applying predominantly direct microwave heating technique led to remarkable physical-mechanical and thermal properties and excellent energy efficiency.

Another performance manufacturing method of a building material different from cement-based ones is the geopolymerization method based on activating alumina-silicate waste in an alkaline aqueous solution. The authors' team of the current work chose a different type of foaming agent (sodium perborate) compared to the traditional agent (hydrogen peroxide). The performance of the insulating properties of the geopolymer was excellently correlated with a high compressive strength.

5. Conclusions

Currently, numerous innovative techniques were designed and experimentally tested in the world aiming at the profitability and greening the porous building materials production processes. Authors' team of the current paper has been involved in such efforts aimed at choosing materials (generally wastes), whose preparation requires very low energy consumption as well as significantly reducing the carbon footprint. Among the new high-performance techniques exposed in the literature, a major contribution of the team came from adopting the unconventional method of microwave heating in processes based on high-temperature sintering the raw material mixture in order to produce cellular glass as a thermal insulation material for construction. Also, it should be mentioned numerous experiments carried out in the field of geopolymer production, involving the choice of unused or little-used alumina-silicate wastes in current manufacturing recipes for these remarkable state-of-the-art materials.

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CONTRIBUȚII PROPRII LA REALIZAREA MATERIALELOR DE
CONSTRUCȚIE POROASE ÎN CONDIȚII ECONOMICE ȘI PRIETENOASE
FAȚĂ DE MEDIU: O TRECERE ÎN REVISTĂ

(Rezumat)

Lucrarea trece în revistă principalele tehnici moderne de fabricare a materialelor de construcție poroase prezentate în literatura de specialitate și contribuția echipei autorilor români ai prezentei lucrări la dezvoltarea lor experimentală. Studiul se referă la metode importante aplicate în ultimele decenii în lume, care au influențat semnificativ

adoptarea unor procedee mai eficiente din punctul de vedere al costurilor și mult mai ecologice. În producția de sticlă celulară au fost aplicate tehnici inovatoare prin sinterizare-spumare la temperatură înaltă, cea mai importantă fiind utilizarea microundelor pentru procese de încălzire cu eficiență energetică ridicată. De asemenea, au fost testate și alte îmbunătățiri tehnologice. Prepararea la rece a sticlei celulare prin utilizarea pulberii de aluminiu ca agent formator al porilor și a soluției de activare $\text{Ca}(\text{OH})_2$ a fost aplicată cu succes, în special din punct de vedere energetic. Metode inovatoare recente de producere a betonului geopolimeric din deșeuri aluminosilicatice a fost, de asemenea, în atenția autorilor. Alte tehnici inovatoare, cum ar fi captarea/stocarea CO_2 în beton, amestecarea „într-o singură parte” la fabricarea betonului și transformarea deșeurilor inerte în sticlă puzzolanică, au fost testate împreună cu contribuțiile autorilor.