A Review of Research on The Preparation and Application of Porous Geopolymers

Qingyao Guo[1, 2, *], Yidong Fan[1, 2], Xia Fan[1, 2], Le Wang[1, 2]

[1]School of civil engineering, Central South University of Forestry and Technology, Changsha, 410004, PR China

[2]Hunan Province Key Laboratory of Engineering Rheology, Central South University of Forestry and Technology, Changsha, 410004, PR China

[*] Corresponding author: Qingyao Guo, E-mail address: qingyaoyee@163.com

Abstract

Geopolymers are three-dimensional inorganic polymer networks formed through depolymerization-polycondensation reactions of aluminosilicate raw materials under alkaline or acidic activation. Their chemical structure resembles that of natural zeolites but exhibits amorphous or semi-crystalline characteristics, endowing them with excellent properties such as high mechanical strength, thermal stability, corrosion resistance, and low permeability. Unlike conventional ceramics, their synthesis requires no high-temperature calcination and can incorporate industrial byproducts such as fly ash, slag, and metakaolin, offering both environmental sustainability and economic advantages. Porous geopolymer materials can be further developed by introducing controllable pore structure through physical or chemical foaming technology, which not only retains the excellent properties of geopolymer matrix, but also has multifunctional properties due to the presence of pores, and shows broad application prospects in the fields of building thermal insulation, noise control, and environmental treatment. This paper reviews the physical and chemical preparation processes of porous geopolymers, introduces the applications of porous geopolymers in thermal insulation, sound absorption, adsorption, PH adjustment, etc., and discusses the future research direction of porous geopolymers.

Keywords

Geopolymers; Porosity; Performance effects; Functional applications.

1. INTRODUCTION

Geopolymers, a novel class of green cementitious materials proposed by French scientist Joseph Davidovits in the 1970s, are formed through the reaction of aluminosilicate oxides with alkaline or acidic activators[1]. This process cleaves Si-O and Al-O bonds, releasing silico-aluminate monomers. These monomers undergo polycondensation in the presence of water and activators, initially forming oligomers, which then dehydrate and polymerize into a stable three-dimensional inorganic polymeric network[2,3]. The dense microstructure and strong covalent/ionic bonding within geopolymers endow them with exceptional mechanical strength, high-temperature resistance, chemical durability, and low permeability[4].Compared to traditional Portland cement, geopolymer synthesis avoids energy-intensive high-temperature calcination, typically proceeding at ambient conditions with significantly reduced carbon footprint. Additionally, industrial by-products such as fly ash, slag, and metakaolin can serve as primary raw materials, offering substantial environmental and economic advantages. This aligns with circular economy principles by valorizing waste streams and minimizing resource depletion[5].

Porous geopolymers are composite materials composed of pores of varying sizes and pore walls. The pores are formed by gas generated from foaming agents within the slurry, which become fixed in the matrix during setting and hardening. These pores constitute the majority of the porous geopolymer system. The pore walls consist of hydration products and unreacted raw material particles[6]. The physical properties of porous geopolymers-such as thermal insulation, mechanical strength, and permeability-are determined by the composition, morphology, and size distribution of the pores and pore walls. The pore structure and wall composition primarily depend on the raw materials and their mix design. Geopolymers inherently exhibit exceptional mechanical properties, thermal resistance, and acid/alkali durability[7]. By introducing controlled porosity, porous geopolymers further expand their functional applications, offering advantages such as lightweight construction, enhanced insulation, and tailored adsorption capacity—properties unattainable with conventional dense materials. Moreover, their chemical stability and eco-friendly synthesis align with sustainable development goals[8]. This paper systematically reviews current preparation methods for porous geopolymers and summarizes their application status, aiming to facilitate the future development of geopolymer technology.

2. PREPARATION OF POROUS GEOPOLYMERS

2.1. Physical Foaming Method

Introducing air bubbles or pores into geopolymer pastes primarily involves physical or chemical foaming techniques. Physical foaming employs mechanical means to incorporate bubbles, including mechanical stirring, high-pressure gas injection, and surfactant pre-foaming. Common foaming agents include rosin-based, synthetic, protein-based, and composite types.

Gu[9] et al. prepared composite foaming agents by mixing sodium dodecyl sulfate, xanthan gum, and water in specific mass ratios. Prefabricated foam was generated using an air compression method and blended with slag-fly ash-based geopolymer paste.Hui[10] et al. prepared fly ash-slag based geopolymers using polyoxyethylene alkyl ether sulfate (PAS) as a pre-foaming agent, and investigated the performance of both foamed (G-1, G-2) and non-foamed (G-0) geopolymers at temperatures ranging from 29 to 1000℃. The incorporation of PAS foam resulted in a 35%-46.9% reduction in compressive strength of the geopolymers. After heat treatment, the compressive strength of G-0 decreased by 7.6-33.9%.

He[11] et al. investigated foam stability using sodium α-olefin sulfonate (AOS), sodium dodecyl sulfate (K12), and sodium alcohol ether sulfate (AES) with FM-500 silicone-polyether emulsion as a stabilizer. AOS demonstrated superior foam stability, producing foam concrete with the highest compressive strength. After mixing with geopolymer paste, AOS-based foams exhibited narrower pore size distributions (mostly <400 μm) and smaller average pore sizes compared to K12 and AES, though all three foams showed similar pore circularity.

Nadeem[12] et al. synthesized geopolymer foam (GPF) via microwave irradiation using natural soil as an aluminosilicate precursor mixed with sodium silicate. Sample GPF50 achieved a thermal conductivity of 0.2387 W/(m·K), total porosity of 76.89%, bulk density of 0.44 g/cm^3, and compressive strength of 3.10 MPa. Sample GPF75 exhibited the highest compressive strength (8.83 MPa) with a total porosity of 37.82%.

2.2. Chemical foaming Method

Chemical foaming involves adding chemical reagents to geopolymer pastes, which release gas through reactions or decomposition to form bubbles. This method typically induces expansion during mixing and resting stages, with limited suitability for cast-in-place applications.

Chemical foaming agents are categorized into organic and inorganic types. Inorganic chemical foaming agents commonly used in geopolymers include:

(1) Metal powders: Primarily aluminum powder (Al) and zinc powder (Zn), which react in alkaline environments to generate hydrogen gas. Ibrahim[13] et al. synthesized porous geopolymers using silica fume and zeolitic tuff as raw materials activated by sodium hydroxide and sodium silicate solutions, with aluminum powder and sodium dodecyl sulfate (SLS) as additives. The resulting materials exhibited high porosity (64.36%–81.32%), low thermal conductivity (0.29–0.07 W/m·K), and sufficient compressive strength (0.96–2.71 MPa). Yatsenko[14] et al. produced slag-based geopolymers with 3% zinc powder, achieving a density of 331 kg/m^3, thermal conductivity of 0.0710 W/(m·K), and compressive strength of 1.17 MPa. Compared to hydrogen peroxide and aluminum powder, zinc powder reacts more slowly, yielding a more uniform porous structure.

Al is a foaming agent with a relatively fast reaction rate. Compared to Zn, the same molar amount of Al releases 50% more hydrogen. When Zn comes into contact with an alkaline activator solution, it produces a smaller amount of gas. To achieve the same foaming density level as Al, the dosage of Zn needs to be six times higher than that of Al[15].

(2) Sodium hypochlorite: Sodium hypochlorite (NaOCl) generates oxygen through self-dissociation or reacts with carbon in geopolymer precursors to produce carbon dioxide. Böke[16] et al. synthesized foamed geopolymers using fly ash, NaOH, and NaOCl as a novel foaming agent at a moderately elevated temperature (90°C). NaOCl prevents premature foaming of the slurry before molding and allows foaming rate control via heating. However, the porosity and strength of the geopolymer may be adversely affected by sepiolite crystals formed during NaOCl dissolution. This drawback necessitates that materials foamed with NaOCl must prevent direct water flow exposure.

(3) Hydrogen peroxide: Hydrogen peroxide (H_2O_2), a thermally unstable compound, decomposes into water and oxygen at ambient temperatures, with its decomposition further accelerated in the alkaline environment of geopolymer synthesis. Compared to metal powders, H_2O_2 enables slower and more controllable foaming, producing only water and oxygen as decomposition products without residual by-products, whereas aluminum powder generates both hydrogen gas and aluminum oxide (Al_2O_3) during foaming. H_2O_2 also ensures more uniform foam distribution in geopolymer pastes, favoring the formation of closed-cell pores and optimized pore structures. Matalkah[17] et al. investigated the effects of H_2O_2 dosage (2.5%-10%) and curing temperatures on physical properties, mechanical characteristics, and pore distribution. The resulting porous geopolymers exhibited bulk densities of 0.46–1.25 g/cm^3 and porosities of 45.2%-87.4%.

(4) Silica fume and silicon-containing compounds: Silicon powder or silicon-containing compounds such as FeSi and SiC react in alkaline environments to release hydrogen gas for bubble formation[18,19]. Silica fume, an eco-friendly material primarily composed of amorphous SiO_2, tends to generate oversized pores during foaming. While pore formation kinetics can be modulated by activator type and solution alkalinity, pore sizes remain relatively large. Liu[20] et al. studied the influence of silica fume content and activator type on porous fly ash-based geopolymers foamed with silica fume. Increasing silica fume content reduced density and compressive strength while enhancing porosity and sound insulation performance. At 45% silica fume content and NaOH activation, porosity increased by 3.02-fold.

3. APPLICATION OF POROUS GEOPOLYMER MATERIALS

3.1. Thermal Insulation

The porous structure of porous geopolymer materials endows them with excellent thermal insulation properties. Heat transfer through pores is progressively attenuated, significantly reducing the material's thermal conductivity and thereby providing insulation. Simultaneously, the dense three-dimensional network structure of geopolymers grants porous geopolymer concrete superior mechanical performance and durability, overcoming the issues of low strength and poor durability found in traditional porous concrete insulation materials[21,22].

Novais M R et al. produced a novel porous biomass fly ash-based geopolymer using hydrogen peroxide as a foaming agent. The resulting porous geopolymer exhibited a thermal conductivity as low as 0.107 W/(m·K) and a density of 560 kg/m^3.

Shahedan N F et al. introduced glass microspheres as insulating fillers into the geopolymer system to prepare high-quality composite materials. At a 10% glass microsphere content, the sample achieved a workability of 70 mm, density of 2165 kg/m^3, compressive strengths of 52.58 MPa (28 d), 54.92 MPa (60 d), and 65.25 MPa (90 d), and a water absorption rate of 3.73%. The thermal conductivity decreased from 1.47 W/(m·K) to 1.19 W/(m·K), thermal diffusivity reduced from 1.88 mm^2/s to 1.02 mm^2/s, and specific heat capacity increased from 0.96 MJ/(m^3·K) to 1.73 MJ/(m^3·K).

Wang et al. developed a novel bio-based thermal insulation material using rice husk and metakaolin as raw materials and H_2O_2 as a foaming agent. Experimental results showed that when the mass ratios of rice husk/geopolymer, foaming agent/geopolymer, and pre-wetting water/rice husk were 0.16, 0.09, and 0.5, respectively, the composite achieved optimal performance: a density of 295 kg/m^3, thermal conductivity of 0.107 W/(m·K), compressive strength of 1.92 MPa, water absorption of 64%, and hygroscopicity of 11.3%.

3.2. Acoustic Absorption

The sound absorption mechanism of porous geopolymers primarily relies on their abundant internal pore structure, which dissipates acoustic energy into thermal energy through viscous friction within the pores and thermal conduction losses between air and pore walls. When sound waves reflect off rigid boundaries, part of the acoustic energy transmits back through the material to its surface and radiates into the air, while another portion reflects back into the material's interior. This repeated propagation of sound waves enables continuous energy conversion and dissipation until equilibrium is reached, thereby allowing the material to "absorb" a portion of the acoustic energy.

Stolz J[23] et al. investigated the sound absorption and noise reduction coefficients of alkali-activated fly ash-based porous geopolymers. The materials exhibited high absorption at extreme frequencies (125-250 Hz in the low-frequency range and 4000–6300 Hz in the high-frequency range). However, the absorption coefficient was notably lower ($\alpha = 0.1$) between 500 Hz and 2000 Hz. At a density of 1130 kg/m^3, the highest noise reduction coefficient reached 0.24.

Zhang Z[24] et al. synthesized geopolymer foam concrete (GFC) by partially replacing Class F fly ash with slag and mechanically blending prefabricated foam. Test results showed that the samples demonstrated remarkable sound absorption ($\alpha = 0.7\text{-}1.0$) in the 40-150 Hz low-frequency range. The average sound absorption performance of GFC surpassed that of dense concrete and was comparable to conventional foam concrete.

Gao[25] et al. achieved precise adjustment of the material's average pore size from 2.48 mm to 0.20 mm by modulating the dosage of cetyltrimethylammonium bromide (CTAB). The optimized material exhibited ultrahigh porosity (93.80%), ultralow density (0.086 g/cm^3), low thermal conductivity (0.040 W/(m·K)), and exceptional acoustic performance (sound absorption coefficients of 0.539 at 5000 Hz and 0.809 at 500 Hz under a 50 mm air cavity; sound insulation of 38.6 dB at 2000 Hz), while maintaining moderate compressive strength (0.27 MPa).

3.3. Adsorption Capacity

The widespread use of heavy metals and their alloys, coupled with rapid industrialization, has significantly exacerbated environmental pollution. While the removal of heavy metals from wastewater is critical for environmental protection, recovering and reutilizing these metals aligns with the essential requirements of a green circular economy. Industrial wastewater containing valuable metals such as Cu, Ni, and Co often exceeds national discharge standards. Geopolymers, recognized for their abundant raw materials, low cost, simple synthesis, mechanical robustness, stability, and eco-friendliness, have emerged as efficient adsorbents for water pollutants, combining both chemical and physical adsorption mechanisms[26].

AlZboon[27] et al. compared natural volcanic tuff with synthetic geopolymers for Zn^{2+} adsorption. Geopolymers showed increased Zn^{2+} adsorption with higher temperatures (25-45℃), prolonged contact time, elevated pH (up to 7), and initial concentrations (up to 160 ppm), while adsorption decreased with higher geopolymer dosage.

Liao[28] et al. utilized carbide slag and fly ash as precursors, with H_2O_2 and sodium dodecyl sulfate (SDS) as foaming agents, to synthesize porous geopolymer microspheres. The CaO and $Ca(OH)_2$ from carbide slag activated the fly ash, generating additional C-S-H gel. The microspheres achieved a specific surface area of 63.46 $m^2 \cdot g^{-1}$, regeneration efficiency of 83.20%, and optimal adsorption capacity of 118.48 $mg \cdot g^{-1}$ at pH=5, demonstrating robust heavy metal wastewater treatment capabilities.

Yan[29] et al. synthesized metakaolin-sodium alginate-chitosan composites, achieving Pb^{2+} equilibrium adsorption capacities of 120.45–142.67 mg/g at pH=5 and 25°C. M et al. employed NaOH-activated volcanic tuff foamed with H_2O_2, evaluating Co^{2+} and Ni^{2+} removal under varying conditions. At pH=6 and 180 minutes contact time, the material achieved removal efficiencies of 86.72% and 81.27%, respectively, with maximum adsorption capacities of 3.19 mg/g (Co^{2+}) and 2.40 mg/g (Ni^{2+}), fitting the Langmuir isotherm model.

Novais R M[30] and colleagues utilized fly ash-based geopolymer spheres to adsorb methylene blue from synthetic wastewater. The adsorption performance of these porous geopolymer spheres was influenced by factors such as the initial dye concentration, adsorbent dosage, and contact time. Specifically, the adsorption capacity increased from 1.1 mg/g to 30.1 mg/g as the initial dye concentration rose from 10 ppm to 250 ppm. Additionally, the dye removal efficiency improved from 82.3% to 94.3% when the initial dye concentration was increased to 125 ppm. Notably, the spherical geopolymers exhibited faster adsorption kinetics compared to bulk geopolymers. After eight regeneration cycles, while the adsorption capacity slightly decreased, the removal efficiency of methylene blue remained robust at 83%, demonstrating the material's promising reusability.

3.4. PH Regulation

Residual alkali in geopolymers reacts with atmospheric CO_2, causing efflorescence (white deposits), which compromises aesthetics, durability, and steel reinforcement protection. However, gradual alkali leaching is advantageous for pH regulation in wastewater treatment, stabilizing pH fluctuations.

Novais R M[31] et al. synthesized metakaolin-based (MK-based) and fly ash-based (FA-based) geopolymer microspheres using a suspension curing process. They reported that the pH buffering properties are closely tied to the raw material composition. MK-based microspheres exhibited a high initial OH^- leaching rate on the first day, which rapidly decreased over time, hindering sustained pH regulation. In contrast, FA-based microspheres demonstrated progressive and long-lasting release characteristics, maintaining a narrow pH fluctuation range of 1.6-1.9, with a maximum OH^- leaching capacity of 0.0317 mol/(dm^3·g). In a subsequent study, the authors fine-tuned the alkaline leaching rate by adjusting hydrogen peroxide dosage and solid-to-liquid ratio during geopolymer synthesis. Higher solid-to-liquid ratios promoted slower alkaline release, while increased porosity significantly elevated the initial pH to a more alkaline range while preserving buffering capability[32].

Gameiro[33] et al. utilized fly ash-based geopolymer microspheres (GS) as a replacement for traditional powdered chemical reagents to regulate pH in anaerobic sequencing batch reactors (ASBRs) treating whey wastewater through sustained alkali leaching. They systematically evaluated the effects of GS porosity and dosage on process performance. Experimental results demonstrated that incorporating high-concentration, high-porosity GS increased methane yield by 30% compared to powder additive systems, while also shifting metabolic byproduct distribution by elevating butyrate content and reducing propionate proportion.

4. CONCLUSION

Porous geopolymer materials, by integrating the chemical stability of the geopolymer matrix with the designable functionality of pore structures, overcome the performance limitations of traditional materials, emerging as representative eco-friendly high-performance materials. By regulating porosity and pore architecture, they achieve lightweight construction, high strength, thermal insulation, and efficient adsorption.

Current research predominantly focuses on innovative foaming pathways, while foundational studies on curing mechanisms, adsorption mechanisms, and theoretical frameworks remain underdeveloped, requiring further exploration. Although geopolymers utilize widely available raw materials, primarily bulk industrial waste, the high cost of alkaline activators poses a significant barrier to the practical scalability of porous geopolymers. Future efforts should prioritize seeking alternative materials to enhance their cost-effectiveness and applicability. In the field of building insulation, while current porous geopolymers exhibit moderate strength and satisfactory performance, they have yet to reach optimal performance levels. Further advancements in formulation optimization or processing techniques are essential to develop porous geopolymers with superior mechanical strength.

ACKNOWLEDGEMENTS

This study is financially supported by the Scientific Innovation Fund for Post-graduates of Central South University of Forestry and Technology (No. 2024KMCX016), which are greatly appreciated.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Qingyao Guo: Investigation, Writing original draftpreparation, Validation, Funding acquisition.

Yidong Fan: Methodology, Supervision.

Xia Fan: Investigation, Conceptualization, Methodology.

Le Wang: Methodology, Investigation.

CONFLICTS OF INTEREST OR COMPETING INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

[1] Ducman V., L. Korat, Characterization of geopolymer fly-ash based foams obtained with the addition of Al powder or H2O2 as foaming agents, Mater. Charact. 113 (2016) 207-213.

[2] Kioupis D., A. Zisimopoulou, S. Tsivilis, G. Kakali, Development of porous geopolymers foamed by aluminum and zinc powders, Ceram. Int. 47(18) (2021) 26280-26292.

[3] Jwaida Z., A. Dulaimi, N. Mashaan, M.A. Othuman Mydin, Geopolymers: the green alternative to traditional materials for engineering applications, Infrastructures 8(6) (2023) 98.

[4] Chen K., W.-T. Lin, W. Liu, Effect of NaOH concentration on properties and microstructure of a novel reactive ultra-fine fly ash geopolymer, Adv. Powder Technol. 32(8) (2021) 2929-2939.

[5] Chen S.-k., C.-l. Wu, D.-m. Yan, Y. Ao, S.-q. Ruan, W.-b. Zheng, X.-l. Sun, H. Lin, Relation between drying shrinkage behavior and the microstructure of metakaolin-based geopolymer, J. Zhejiang Univ. Sci. A 22(10) (2021) 819-834.

[6] Khan S., N. Mir, A. Kul, O. Şahin, M. Şahmaran, M. Koç, Renewable energy for carbon footprint reduction of green geopolymers material's production for built-environment, Energy Reports 8 (2022) 852-858.

[7] Yu H., M.x. Xu, C. Chen, Y. He, X.m. Cui, A review on the porous geopolymer preparation for structural and functional materials applications, Int. J. Appl. Ceram. Technol. 19(4) (2022) 1793-1813.

[8] Mendes B.C., L.G. Pedroti, C.M.F. Vieira, M. Marvila, A.R. Azevedo, J.M.F. De Carvalho, J.C.L. Ribeiro, Application of eco-friendly alternative activators in alkali-activated materials: A review, J. Build. Eng. 35 (2021) 102010.

[9] Gu G., F. Xu, X. Huang, S. Ruan, C. Peng, J. Lin, Foamed geopolymer: The relationship between rheological properties of geopolymer paste and pore-formation mechanism, J. Cleaner Prod. 277 (2020) 123238.

[10] Hui-Teng N., H. Cheng-Yong, L. Yun-Ming, M.M.A.B. Abdullah, C. Rojviriya, H.M. Razi, S. Garus, M. Nabiałek, W. Sochacki, I.M.Z. Abidin, Preparation of fly ash-ladle furnace slag blended geopolymer foam via pre-foaming method with polyoxyethylene alkyether sulphate incorporation, Materials 15(12) (2022) 4085.

[11] He J., Q. Gao, X. Song, X. Bu, J. He, Effect of foaming agent on physical and mechanical properties of alkali-activated slag foamed concrete, Constr. Build. Mater. 226 (2019) 280-287.

[12] Nadeem M., E.U. Haq, F. Ahmed, M.A. Rafiq, G.H. Awan, M. Zain-ul-Abdein, Effect of microwave curing on the construction properties of natural soil based geopolymer foam, Constr. Build. Mater. 230 (2020) 117074.

[13] Ibrahim J.E.F.M., E.İ. Şahin, M.A. Basyooni-M. Kabatas, R. Géber, I. Kocserha, Sustainable fabrication of lightweight geopolymer foams from silica-fume and zeolite tuffs: Utilizing Al as foaming agent for thermal insulation, Case Stud. Constr. Mater. 21 (2024) e04024.

[14] Yatsenko E.A., B.M. Goltsman, A.I. Izvarin, V.M. Kurdashov, A.V. Ryabova, Influence of foaming additives on the porous structure and properties of lightweight geopolymers based on ash–slag waste, Constr. Build. Mater. 443 (2024) 137629.

[15] Kränzlein E., H. Pöllmann, W. Krcmar, Metal powders as foaming agents in fly ash based geopolymer synthesis and their impact on the structure depending on the Na /Al ratio, Cem. Concr. Compos. 90 (2018) 161-168.

[16] Böke N., G.D. Birch, S.M. Nyale, L.F. Petrik, New synthesis method for the production of coal fly ash-based foamed geopolymers, Constr. Build. Mater. 75 (2015) 189-199.

[17] Matalkah F., A. Ababneh, R. Aqel, Synthesis of calcined kaolin-based geopolymer foam: Assessment of mechanical properties, thermal insulation, and elevated temperature stability, Ceram. Int. 49(6) (2023) 9967-9977.

[18] Chen D., Y. Zhang, W. Wang, Y. Shi, J. Mao, Y. Liu, D. Yan, S. Chen, Influence of direct foaming methods on the early performance and microstructure of metakaolin-based foam geopolymers, Int. J. Appl. Ceram. Technol. 22(1) (2025) e14848.

[19] Abo Sawan S.E., M.F. Zawrah, R.M. Khattab, A.A. Abdel-Shafi, In-situ formation of geopolymer foams through addition of silica fume: Preparation and sinterability, Mater. Chem. Phys. 239 (2020) 121998.

[20] Liu X., C. Hu, L. Chu, Microstructure, compressive strength and sound insulation property of fly ash-based geopolymeric foams with silica fume as foaming agent, Materials 13(14) (2020) 3215.

[21] Novais R.M., G. Ascensão, N. Ferreira, M. Seabra, J. Labrincha, Influence of water and aluminium powder content on the properties of waste-containing geopolymer foams, Ceram. Int. 44(6) (2018) 6242-6249.

[22] Becker S., M. Michel, P. Mitschang, M. Duhovic, Influence of polymer matrix on the induction heating behavior of CRPC laminates, Compos. B. Eng. 231 (2022) 109561.

[23] Stolz J., Y. Boluk, V. Bindiganavile, Mechanical, thermal and acoustic properties of cellular alkali activated fly ash concrete, Cem. Concr. Compos. 94 (2018) 24-32.

[24] Zhang Z., J.L. Provis, A. Reid, H. Wang, Mechanical, thermal insulation, thermal resistance and acoustic absorption properties of geopolymer foam concrete, Cem. Concr. Compos. 62 (2015) 97-105.

[25] Gao H., H. Liu, L. Liao, L. Mei, F. Zhang, L. Zhang, S. Li, G. Lv, A bifunctional hierarchical porous kaolinite geopolymer with good performance in thermal and sound insulation, Constr. Build. Mater. 251 (2020).

[26] Jarak I., M. Pereira-Silva, A.C. Santos, F. Veiga, H. Cabral, A. Figueiras, Multifunctional polymeric micelle-based nucleic acid delivery: Current advances and future perspectives, Applied Materials Today 25 (2021) 101217.

[27] Al-Zboon K.K., B.M. Al-smadi, S. Al-Khawaldh, Natural Volcanic Tuff-Based Geopolymer for Zn Removal: Adsorption Isotherm, Kinetic, and Thermodynamic Study, Water, Air, Soil Pollut. 227(7) (2016) 1-22.

[28] Liao Y., X. Ma, J. Zou, M. Zhao, D. Chen, D. Xu, B. Yuan, Preparation and adsorption properties of microsphere geopolymers derived from calcium carbide slag and fly ash, Sci. Rep. 15(1) (2025) 7021.

[29] Yan C., L. Guo, D. Ren, P. Duan, Novel composites based on geopolymer for removal of Pb(II), Mater. Lett. 239 (2019) 192-195.

[30] Novais R.M., J. Carvalheiras, D.M. Tobaldi, M.P. Seabra, R.C. Pullar, J.A. Labrincha, Synthesis of porous biomass fly ash-based geopolymer spheres for efficient removal of methylene blue from wastewaters, J. Cleaner Prod. 207 (2019) 350-362.

[31] Novais R.M., M.P. Seabra, J.A. Labrincha, Porous geopolymer spheres as novel pH buffering materials, J. Cleaner Prod. 143 (2017) 1114-1122.

[32] Novais R.M., L.H. Buruberri, M.P. Seabra, D. Bajare, J.A. Labrincha, Novel porous fly ash-containing geopolymers for pH buffering applications, J. Cleaner Prod. 124 (2016) 395-404.

[33] Gameiro T., R.M. Novais, C.L. Correia, J. Carvalheiras, M.P. Seabra, L.A.C. Tarelho, J.A. Labrincha, I. Capela, Role of waste-based geopolymer spheres addition for pH control and efficiency enhancement of anaerobic digestion process, Bioprocess Biosystems Eng. 44(6) (2021) 1167-1183.