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Editorial

Advances in Geopolymer Composites: From Synthesis to Sustainable Applications

Shima Pilehvar [1,*] and Luís G. Baltazar [2,*]

[1] Faculty of Engineering, Østfold University College, P.O. Box 700, 1757 Halden, Norway
[2] Department of Civil Engineering and CENIMAT, NOVA School of Science and Technology (FCT NOVA), 2829-516 Caparica, Portugal
* Correspondence: shima.pilehvar@hiof.no (S.P.); luis.baltazar@fct.unl.pt (L.G.B.)

The increasing demand for sustainable construction materials has brought significant attention to geopolymers as a viable alternative to traditional Portland cement. Portland cement production is a major contributor to CO_2 emissions, accounting for about 8% of man-made CO_2 emissions [1]. In recent years, geopolymers have gained significant attention from researchers and engineers as a promising environmentally friendly alternative to traditional Portland cement binders [2,3]. Geopolymers are formed through the reaction between an aluminosilicate source and an alkali activator, resulting in materials with superior mechanical properties, and better resistance to acid attacks, high temperatures, and fire. Geopolymers offer a greener solution with approximately 73% lower greenhouse gas emissions and 46% lower energy consumption compared to Portland cement [4]. This Special Issue of the *Crystals* journal, titled "Geopolymer Composites", brings together innovative research that advances our understanding of geopolymer technology and explores its diverse applications. The articles included provide comprehensive insights into the synthesis, characterization, performance, and environmental impact of geopolymer composites.

New alternative raw materials and their subsequent use for supporting the sustainability of natural resources are one of the main factors in the design of geopolymers. Ivana et al. [5] investigate the incorporation of different waste stone powders (WSP) into the synthesis of metakaolin-based geopolymer composites. This study shows that WSPs slightly improve the mechanical and textural properties of geopolymers and act as accelerators, reducing the setting time. This research suggests that WSP, which would otherwise be landfilled, can be effectively used in geopolymer production, contributing to environmental sustainability by reducing waste. Similarly, Sood et al. [6] demonstrate the feasibility of producing alkali-activated mortars (AAMs) using industrial wastes such as fly ash and ground granulated blast furnace slag (GGBFS). This study highlights that binary combinations of these materials achieve higher mechanical properties than ternary mixtures. The research confirms that cement-free AAMs with satisfactory mechanical and durability properties can be developed from these industrial waste materials. Nduka et al. [7] explore the use of rice husk ash (RHA) as a partial replacement for cement in high-performance concrete (HPC). This study shows that RHA significantly enhances durability properties, including water absorption, sorptivity, and resistance to chemical attack. These findings support RHA as a beneficial and cost-effective agro-waste resource for sustainable concrete technology.

Baltazar [8] examines the fresh and hardened properties of silica fume (SF)-based geopolymer grouts for the consolidation of old stone masonry. While these grouts initially show poorer rheological properties compared to natural hydraulic lime (NHL) grouts, the addition of a polycarboxylate-based superplasticizer (SP) significantly improves fluidity. Adjusting the alkali content enhances the grout's spread and density, and the SF-based geopolymer grout exhibits a significant increase in adhesion strength, which is crucial for masonry consolidation. Alanazi's study [9] highlights the impact of aggregate type on the mechanical properties of geopolymer concrete (GP) and traditional Portland cement (TC)

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concrete. The research finds that GP with limestone aggregates forms well-bonded regions between paste and aggregate, whereas GP with quartz aggregates forms weak interfacial zones. The mechanical properties of GP are highly sensitive to aggregate stiffness and stress concentration. Javed et al. [10] study concrete-filled double-skin tubular columns, finding that replacing the inner steel tube with a PVC pipe offers a cost-effective alternative with minimal strength reduction. The experimental results suggest that existing design methods can accurately predict the performance of these columns.

In terms of thermal performance, Lu et al. [11] investigate the microstructural evolution of metakaolin-based K geopolymer at high temperatures. The research reveals that the geopolymer becomes porous as the temperature increases, with pores closing and leucite crystallizing at higher temperatures. This study highlights the potential of using aluminosilicate solid wastes, like red mud and slags, in high-temperature applications.

According to the findings of Martauz et al. [12], hybrid alkali-activated cement, using by-products like steel slag and air-cooled slag, can effectively replace natural aggregates in concrete production. This study shows that concrete made with H-CEMENT increases in strength under outdoor conditions, while Portland blended cement exhibits a decrease in strength. The combination of H-CEMENT with PUZZOLANIT mitigates the loss of strength, suggesting that these materials are suitable for creating durable, eco-friendly concrete. Wang et al. [13] demonstrate that marble waste powder enhances the early strength of cementitious materials, particularly with finer particles. The research supports the use of marble waste powder to improve the mechanical properties and microstructure of cementitious materials, thus contributing to sustainable development by recycling waste stone powder. Novotná et al. [14] enhance the photocatalytic activity of geopolymers by incorporating industrially produced TiO_2 powders. These geopolymers effectively degrade Rhodamine B dye, a common textile industry pollutant, making them suitable for wastewater treatment and air purification.

This Special Issue on "Geopolymer Composites" in the *Crystals* journal provides a comprehensive overview of the latest advancements in geopolymer technology. The contributions highlight significant progress in understanding the fundamental properties of geopolymers, improving their performance, and expanding their applications. As the demand for sustainable and durable construction materials grows, geopolymers are poised to play a crucial role in the future of the construction industry.

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