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Optimizing the Composition of Geopolymer Composites Incorporating Secondary Aluminium Industry By-Products Using Mathematical Modelling

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ABSTRACT

Geopolymer composite materials are a viable alternative to conventional construction materials. The research problem of geopolymer composites revolves around the imperative to comprehensively address their synthesis, structural performance, and environmental impact. The derived mathematical model facilitates precisely determining the optimal proportions of two crucial constituents in the geopolymer matrix: silica sand and secondary aluminum by-product. A mathematical model for optimizing the composition of geopolymer composites has been developed based on the integrated use of Markov chains, criterion methods, and an orthogonally compositional plan. The optimal composition of the geopolymer matrix is determined and predicted using a mathematical model. Specifically, the recommended content mixing ratio is as follows: metakaolin at 1000 g, activator at 900 g, silica fume at 1052.826 g, carbon fibre at 10 g, and secondary aluminum by-product at 62.493 g. This study analyzes the influence of different secondary aluminum industry by-products on the geopolymerization process and assesses the mechanical, thermal, and environmental properties of the resulting composites to establish a comprehensive understanding of their structural viability.

OBJECTIVES

The primary **goal** of this research was to **develop a mathematical and experimental methodology** for **optimizing the composition of geopolymer composites** by analyzing the **combined influence** of *quartz sand* and *secondary aluminum industry by-products (C.FG)*.
This dual-variable approach represents a significant step beyond traditional single-factor analyses, enabling **digital prediction** of optimal compositions through **multi-criteria optimization**, **Markov chains**, and **orthogonal compositional planning**.

Experimental Approach

The study involved systematic preparation of geopolymer composites containing **metakaolin, alkaline activator, silica sand, carbon fibres,** and **aluminum by-product**. Mechanical, thermal, and physical tests were carried out to generate data for the optimization model.

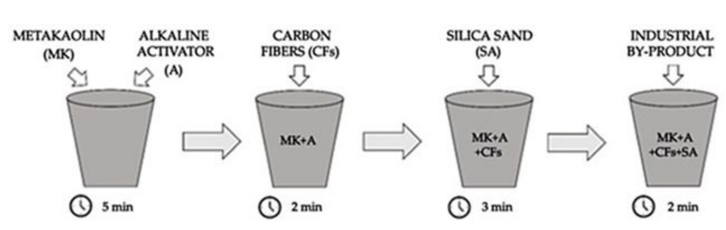

Fig. 1 *Preparation process of the test samples*

Research Workflow

A **hybrid experimental–computational procedure** was established to minimize the number of physical tests and enhance prediction accuracy.
The research flow chart illustrates the integration of:

- Laboratory measurements
- Mathematical modelling
- Statistical and probabilistic optimization

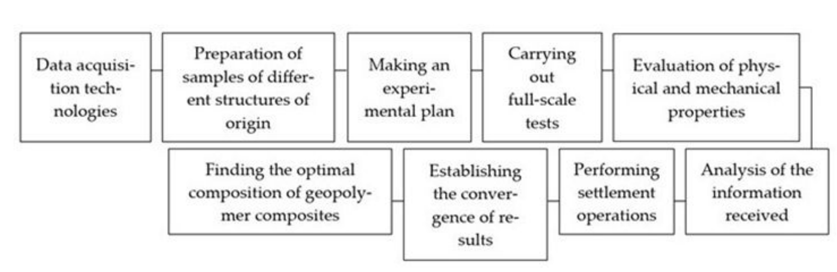

Fig. 2 *Research flow chart*

Model Development

Using **Markov chain analysis**, weight coefficients were assigned to each criterion: **compressive strength (0.313)**, **bending strength (0.233)**, **impact strength (0.162)**, **density (0.148)**, **thermal conductivity (0.144)**.
This allowed for an **objective ranking** of parameters and the transformation of complex experimental data into a single optimization index.

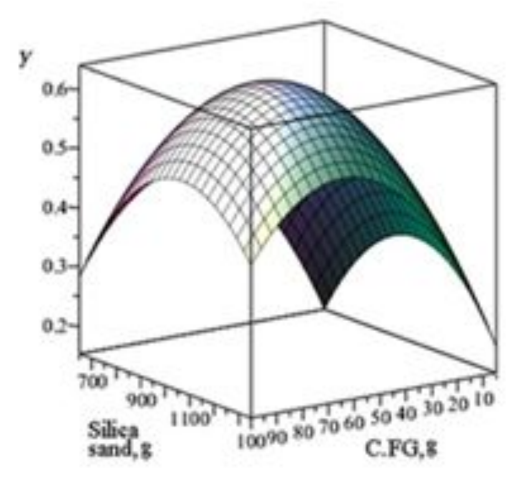

Fig. 3 *Response surface of the model*

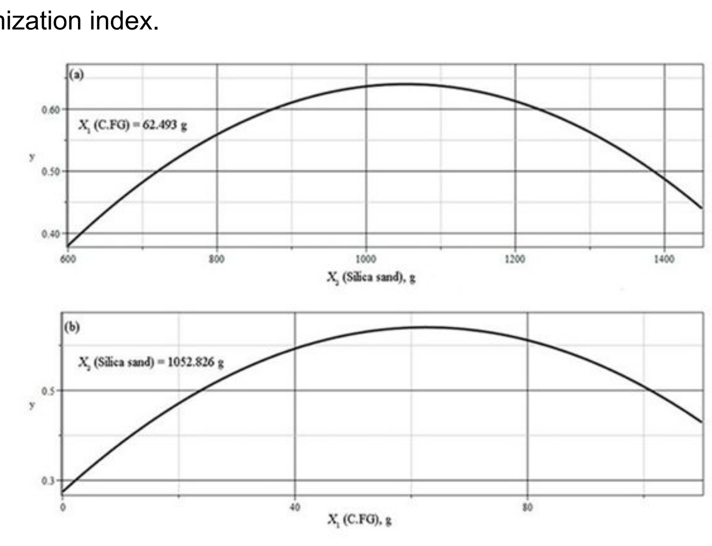

Fig. 4 *Cross-sections of the model response surface*

Scientific and Practical Impact

The developed model allows visualization of how **C.FG** and **silica sand** simultaneously affect mechanical and thermal properties.
It provides a **powerful tool for material design**, enabling:

- **Reduction of laboratory workload**
- **Digital optimization of mixture composition**
- **Enhanced prediction of material performance**

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CONCLUSIONS

The presented model of geopolymer foam production technology for two-component variability of geopolymer matrix composition allows us to determine the formulation point where the proportions of each component in the geopolymer matrix are optimally combined. The presented mathematical model can serve as a reliable tool for controlling the structure formation of two-component complex systems. The advantage of the developed optimization model is the possibility of visualizing the dynamics of the relationship between the responses to changes in the studied structural components. The study's findings may inform industry practices by offering a novel avenue for the utilization of secondary aluminum by-products, promoting resource efficiency and waste valorisation. The study's significance extends to its potential to drive innovation in the construction sector, promoting the adoption of greener technologies and practices.

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