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Assessment of Durability and Degradation Resistance of Geopolymer Composites in Water Environments

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ABSTRACT

This article presents experimental studies on the characterization of geopolymer composites intended for applications in aquatic environments, with particular emphasis on underwater infrastructure. The motivation for conducting the research was the growing need to develop durable and ecological building materials that will be resistant to long-term exposure to moisture and aggressive chemical agents, typical for the underwater environment, where traditional cement concretes undergo gradual degradation due to long-term water impact, including hydrotechnical and underwater infrastructure. Geopolymer binders were produced based on metakaolin activated by alkaline solutions containing sodium hydroxide. Several series of mixtures with additives such as blast furnace slag, amphibolite and carbon fibers were developed to evaluate the effect of these components on mechanical strength, water absorption and chemical durability. The tests conducted showed that the addition of slag improved the mechanical properties, achieving the best composition of 50 MPa. In contrast, the addition of amphibolite had an unfavorable effect, which probably results from introducing inhomogeneity into the material structure. The presence of carbon fibers promoted matrix cohesion, but their uneven distribution could lead to local strength ferences. Water absorption tests have shown that geopolymers reach full water saturation within 24 to 48 h, which indicates rapid establishment of capillary equilibrium and limited further water penetration. The conclusions from the work indicate that geopolymer composites with a moderate amount of blast furnace slag and subjected to appropriate curing conditions. High strength, water and chemical resistance make them suitable for, among others, the construction of marine foundations, protection and structural shields of submerged applications.

OBJECTIVES

The main **goal** of this study was to **evaluate the durability and chemical resistance** of **geopolymer composites** designed for **underwater and aquatic infrastructure applications**.
The research aimed to **identify compositions** capable of maintaining **mechanical integrity** and **low water absorption** when exposed to aggressive environmental conditions such as **acidic, alkaline, and saline solutions**.

This work supports the development of **eco-efficient, long-lasting alternatives to Portland cement**, particularly for **hydrotechnical structures, marine constructions**, and **protection of underwater infrastructure** such as shipwrecks or pipelines.

Research Focus

The study investigated **metakaolin-based geopolymer binders** activated with **sodium hydroxide and water glass**, enhanced by **blast furnace slag, amphibolite**, and **carbon fibers**. These additives were selected to explore how **mineral and fiber reinforcements** affect **mechanical strength, porosity, and chemical resistance** in aquatic exposure.

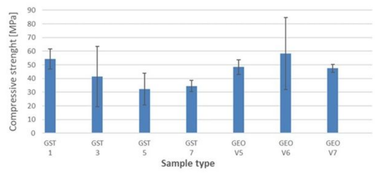

Fig. 1 *Preparation process of geopolymer samples (composition scheme)*

Experimental Design

Seven different compositions were synthesized and tested for **density, compressive strength, water absorptio**
Samples were exposed for **30 days** to various environments:

- **Distilled water**,
- **NaCl solution (salt water)**,
- **HCl (acidic medium)**,
- **Mixture of HCl + HNO_3 + CH_3COOH (multi-acid solution)**,
- **NaOH (alkaline medium)**.

Analytical Approach

To understand degradation mechanisms, advanced techniques were applied:

- **FTIR** – to detect chemical bond changes (Si–O–Al, Si–O–Si),
- **SEM** – to visualize microstructural alterations,
- **XRF** – to analyze elemental composition and track leaching effects.

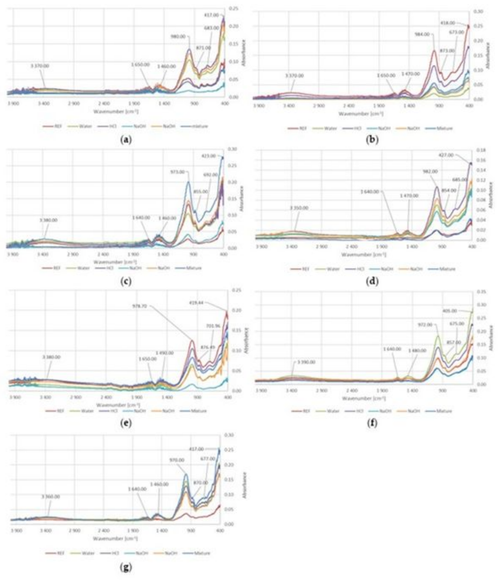

Fig. 3 *FTIR spectra illustrating bond degradation under acidic exposure*

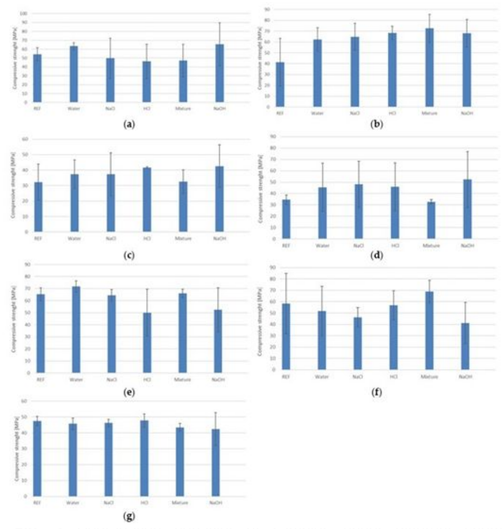

Fig. 2 *Degradation behavior of samples under different chemical environments.*

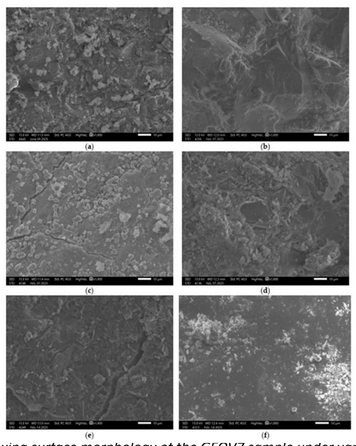

Fig. 4 *SEM micrographs showing surface morphology of the GEOV7 sample under various conditions*

Key Findings

- **Slag addition** significantly improved **compressive strength** (up to 50 MPa) and **chemical resistance**.
- **Amphibolite** addition had a **negative impact** on microstructure, likely due to heterogeneity and increased porosity.
- **Carbon fibers** improved **matrix cohesion**, though uniform dispersion was critical to avoid local weaknesses.
- **Water absorption equilibrium** was reached within **24–48 hours**, indicating rapid stabilization and limited long-term permeability.
- The **GEO V5 and GEO V6** compositions exhibited **optimal durability** and **minimal degradation**, making them suitable for underwater use.

CONCLUSIONS

The conducted research demonstrated that **geopolymer composites with a high content of ground granulated blast furnace slag (GGBFS)** and without the addition of amphibolite—specifically the compositions **GST 1** and **GEO V6**—proved to be the most suitable for underwater and water-exposed applications. These materials exhibited a **favorable combination of low water absorption, high compressive strength, and excellent chemical stability**, making them promising candidates for use in **marine construction, hydraulic engineering, and structures exposed to aggressive aqueous environments**.

The results clearly indicate that **increasing the proportion of blast furnace slag** in the geopolymer matrix contributes to the formation of a denser and more homogeneous microstructure. This leads to **enhanced mechanical performance**, particularly in terms of compressive strength. The **optimal mechanical parameters** were achieved when the slag content reached **50% of the total binder mass**, which provided a well-balanced system between strength, workability, and durability.

Conversely, the **addition of amphibolite** to the geopolymer mixtures was found to have a **detrimental effect on compressive strength**, likely due to reduced reactivity and weaker bonding between the matrix and the filler particles. Although the inclusion of amphibolite and slag resulted in a **slight increase in water absorption**, this effect was not significant enough to compromise the overall integrity of the material, particularly under submerged conditions.

Spectroscopic analysis using **Fourier Transform Infrared Spectroscopy (FTIR)** confirmed the formation of characteristic bands typical of geopolymeric materials. These spectra are indicative of the **Si–O–Al and Si–O–Si bond structures**, confirming the successful polymerization processes within the geopolymer matrix and the development of stable aluminosilicate frameworks.

Based on the comprehensive evaluation of mechanical, physical, and chemical parameters, it can be concluded that the **tested slag-based geopolymer composites** possess the necessary characteristics for **use in aquatic and marine environments**, including underwater structural elements, protective coatings, and repair mortars. Their combination of **high durability, low permeability, and chemical resistance** positions them as a sustainable and effective alternative to traditional cementitious materials in environments exposed to continuous or intermittent water contact.

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