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Reactivity and structural characteristics of plasma-derived wind turbine blade slag in geopolymer systems

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INTRODUCTION & AIM

SITUATION

By 2050, around 43 million tons of wind turbine blade waste (WTBW) are expected globally.

Most blades are landfilled after 20–25 years of service due to limited recycling options.

PROBLEM

Wind turbine blades are mainly composed of glass fiber-reinforced polymers (GFRP) containing 80–90% glass fibers.

Their cross-linked fiber–polymer structure makes them highly durable but difficult to recycle, and conventional mechanical recycling methods are inefficient.

INOVATION

Thermal plasma treatment offers a promising alternative, converting WTBW into plasma-melted (vitrified) slag while recovering valuable resources, supporting circular economy and sustainable resource use.

AIM

To examine plasma-vitrified WTBW slag as a potential reactive aluminosilicate precursor for phosphate geopolymer binders through analysis of its structure, phase composition, and chemical stability testing.

METHOD

Innovative Solution: Plasma Degradation Technology

The main operational parameters of the plasma-chemical system	
Plasma torch power, kW	60
Total gas flow rate, g/s	15
The average gas flow temperature, K	2800
The average gas flow velocity, m/s	180
WTBW feed rate, kg/h	4,7

Vitrified slag valorization in geopolymers

Chemical stability test

The chemical stability of vitrified slag (VS) was evaluated by immersing it in two solutions that simulate the hardening media of geopolymers:

- **Acidic solution:** 8 M H_3PO_4
- **Alkaline solution:** Sodium silicate–NaOH (with a SiO_2/Na_2O ratio of 2.8)

Phosphate-based geopolymers were prepared using metakaolin as the primary precursor, with 5 wt% of metakaolin replaced by vitrified slag. Two types of metakaolin were used:

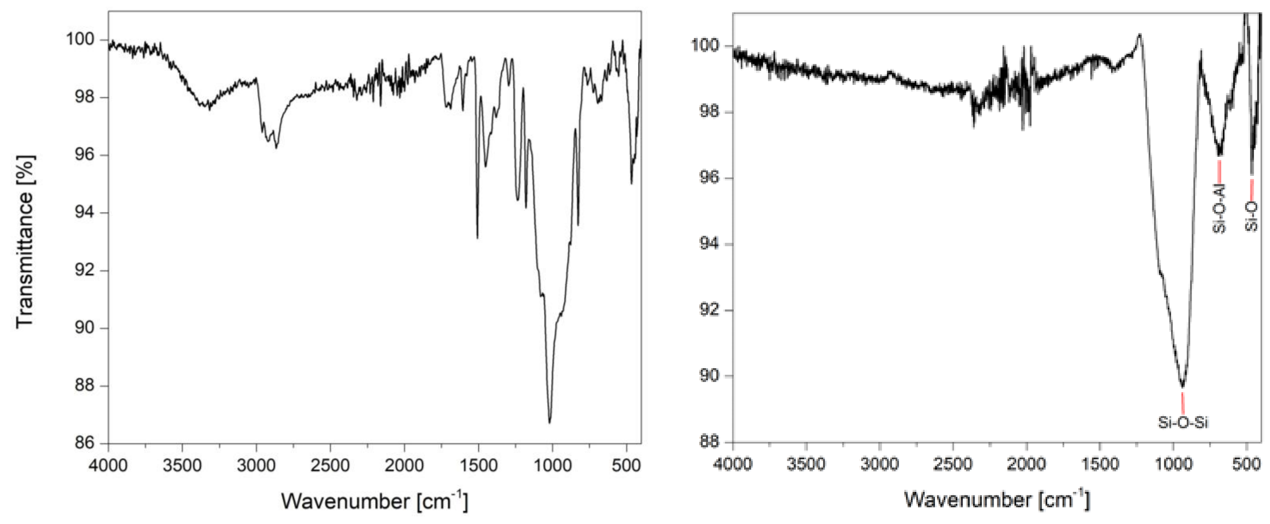
- **MK1** – derived from **kaolinitic clay (K1)**
- **MK2** – derived from **kaolinitic–illitic clay (K2)**

The clays were **calcined at 800 °C for 2 hours.**

The **Si/P ratio of geopolymers** was maintained at a nearly constant level across all mixtures to ensure comparable geopolymerization conditions.

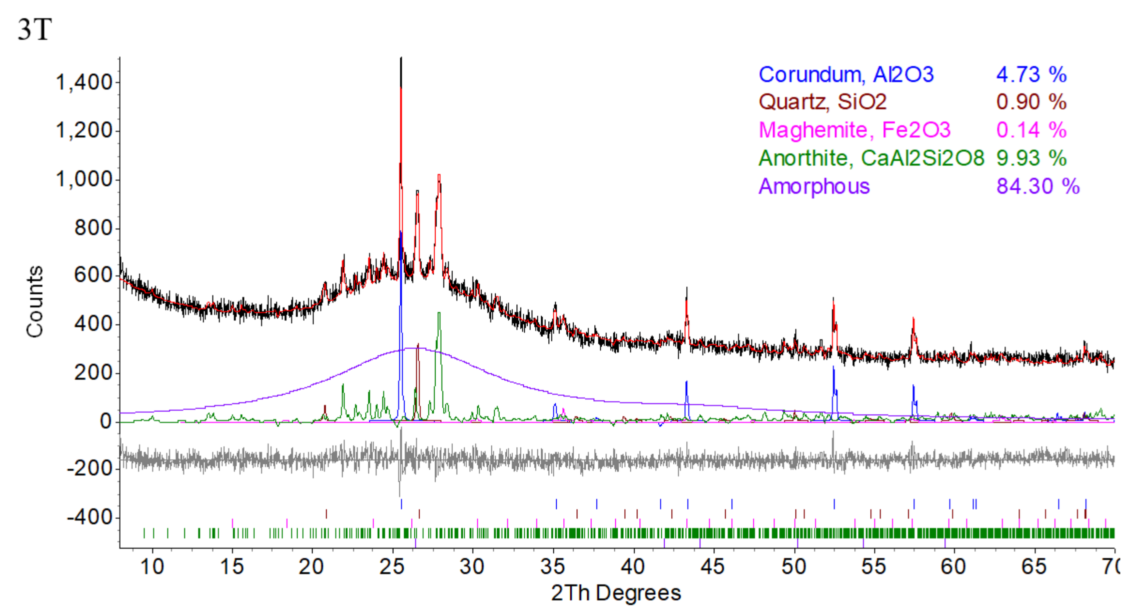
RESULTS & DISCUSSION

Comparison of **FTIR spectra** indicates that virgine wind turbine blades contain various organic chemical bonds, while plasma-vitrified slag primarily consists of SiO_2, CaO, and Al_2O_3, making it a potential precursor for geopolymer.

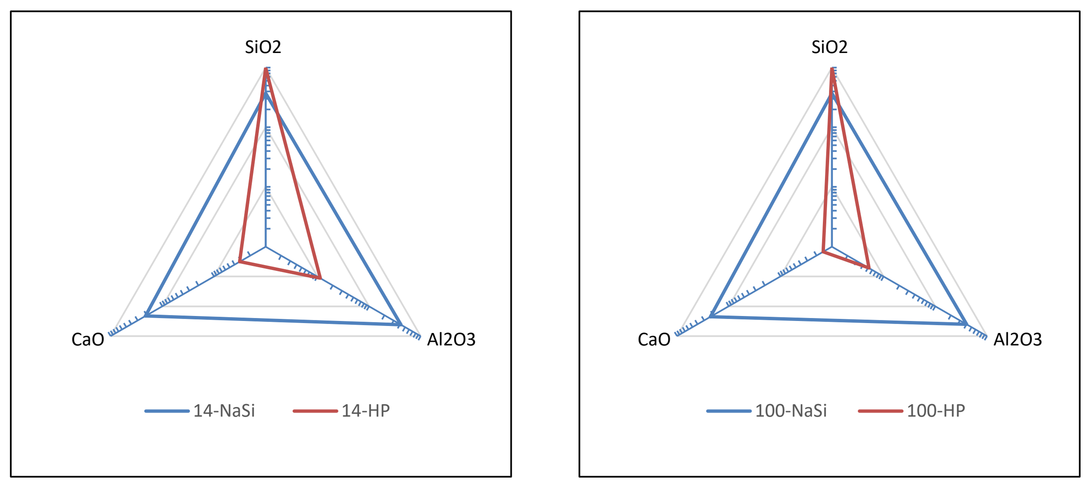


XRD analysis of plasma-treated slag showed predominantly amorphous VS, with a crystalline fraction of approximately 10%.

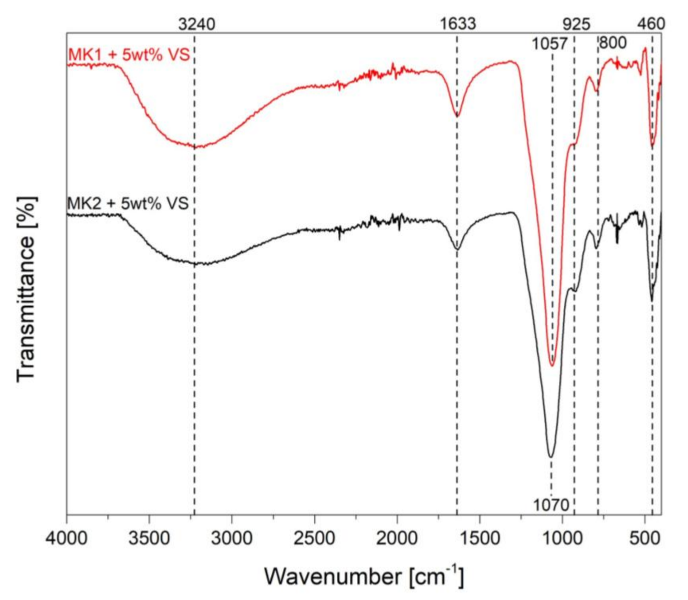
The amorphous–crystalline balance is a key factor determining the reactivity and suitability of plasma-derived slag as a geopolymer precursor.



Chemical stability tests of VS demonstrated selective dissolution of Ca and Al in phosphoric acid, leading to the formation of a silica-rich residual structure, while alkaline exposure caused only limited surface reorganisation.



New Opportunities for Geopolymer Additives

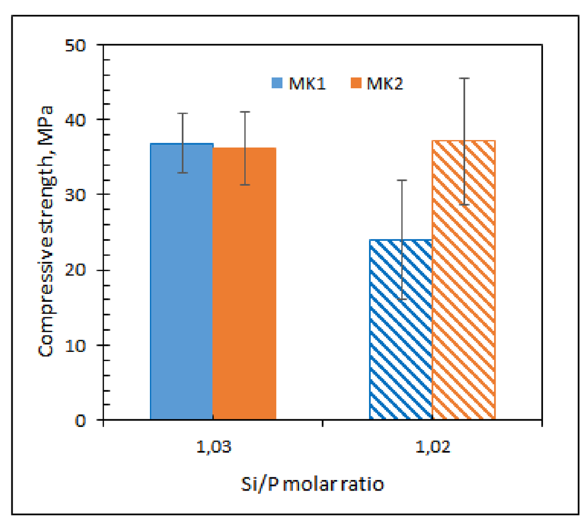


Effect of Phosphoric Acid Concentration on Geopolymer Structure

The prominent absorption band centered at approximately 1000 cm^{-1} is attributed to the asymmetric stretching vibrations of Si–O–T (where T = Si, Al, or P) units, characteristic of the geopolymer network. There may also be overlapping contributions from P–O–Si and P–O–Al linkages in this region, particularly at higher phosphoric acid concentrations.

Mechanical testing

Incorporating amorphous vitrified slag (VS) as a partial substitute for calcined kaolinitic/illitic clay resulted in significant changes in the strength of acid-based geopolymers. Strength of geopolymer with MK1 reduced up to 35%. Contrary, the strength of geopolymer with MK2 remained unchanged, although 5% of MK2 was replaced by VS. *Results highlight the importance of clay selection* for geopolymers production with the incorporation of vitrified slag.



CONCLUSION

- Plasma vitrification enables the transformation of wind turbine blade waste into chemically stable, reactive slag, offering a promising circular pathway for the valorization of composite waste.
- The combined XRD, FTIR, and SEM-EDS analyses provided detailed insight into the phase composition, structure, and microstructure, confirming the suitability of vitrified slag for geopolymer applications.
- The results demonstrate the potential of vitrified slag in phosphate geopolymer systems and provide a foundation for further research, particularly using MK2 metakaolin and higher slag replacement levels.

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