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Design and Functionalization of Red Mud–Derived Mesoporous Sorbent for CO_2 Adsorption

HUI-YEON KIM[1], DONG-WAN CHO[2] AND HYEOP-JO HAN[2]

[1]Korea institute of Geoscience and mineral resources
[2]Korea Institute of Geoscience and Mineral Resources

This study is positioned as a fundamental investigation into mineral-based CO_2 sorbents, with the objective of establishing design principles for functionalized mineral materials rather than pursuing immediate industrial deployment. Mineral-derived materials are attractive platforms for CO_2 capture research due to their abundance, structural stability, and tunable surface chemistry. In this context, red mud (RM), an alkaline industrial by-product of alumina production via the Bayer process, was selected as a representative mineral-rich residue to explore its potential as a functional support for CO_2 adsorption.

Globally, RM is generated at a scale of approximately 300 million tons per year, yet its reuse rate remains below 3%. Its disposal presents significant environmental challenges owing to its high alkalinity, salinity, and fine particle size. Accordingly, this work focuses on transforming RM from an environmentally problematic residue into a functional mineral platform for CO_2 capture studies.

To enhance its suitability as a sorbent support, RM was structurally modified through acid digestion, alkali reprecipitation, and calcination. This treatment generated a mesoporous framework and increased the BET surface area from 17.47 to 140.05 m^2/g, producing a well-defined mineral matrix with controlled porosity. The resulting activated RM (ARM) enables systematic investigation of interactions between immobilized nitrogen-containing functional groups and CO_2.

Amine- and guanidine-functionalized sorbents were prepared by wet impregnation using polyethylenimine (PEI), triethylenetetramine (TETA), and 1,5,7-triazabicyclo[4.4.0]dec-5-ene (TBD). FT-IR spectroscopy, thermogravimetric analysis, and elemental analysis confirmed the successful immobilization of these functional groups, providing a robust platform for mechanistic interpretation.

CO_2 adsorption experiments were conducted in a fixed-bed reactor under mild conditions to evaluate sorbent performance and structure–function relationships. Among the tested materials, ARM–TETA exhibited the highest CO_2 adsorption capacity (36.90 mg/g), underscoring the importance of molecular flexibility and amine accessibility within mesoporous mineral frameworks.

Overall, this work presents a baseline study for mineral-supported CO_2 sorbents, demonstrating how alkaline industrial mineral residues can be engineered into well-defined model systems for adsorption research. The findings offer fundamental insights into the interplay between pore structure and surface functionality, contributing to the rational design of next-generation mineral-based CO_2 capture materials.