Technical Validation of Batch Carbonation of Construction Waste in a Semi-Industrial Spouted Bed Reactor

Introduction

Carbon dioxide capture remains one of the main technological challenges associated with industrial decarbonization. Among the available approaches, mineral carbonation has attracted growing interest due to its ability to permanently bind CO_2 into thermodynamically stable carbonates while simultaneously enabling the valorization of alkaline industrial residues. Mineral carbonation processes based on calcium-bearing compounds have been extensively reviewed in the literature as promising long-term sequestration strategies (Sanna et al., 2014). In particular, calcium-rich construction and demolition wastes represent an attractive feedstock because of their intrinsic carbonation potential and their availability in large volumes, as previously explored in cement kiln dust and related residues (Huntzinger et al., 2009).

This work presents the technical validation of HECO (High Efficiency Contact) technology for CO_2 capture through direct carbonation of construction waste in a semi-industrial batch process. The technology is based on a truncated conical spouted bed reactor specifically designed to intensify gas–solid contact and improve reaction efficiency. The reactor concept builds on previous modeling and experimental studies of fluidized and carbonator systems for post-combustion CO_2 capture (Alonso et al., 2009). The study focuses on validating reactor performance under representative flue gas conditions and on developing a reliable methodology to quantify the degree of carbonation in heterogeneous mineral residues.

Methodology

The evaluation of carbonation efficiency in solid materials requires careful analytical treatment, as performance cannot be assessed solely through gas composition measurements. A wide range of qualitative and quantitative techniques have been proposed in the literature to determine the degree of carbonation in cementitious and mineral systems (Ledésert et al., 2009; Bui et al., 2023). For this reason, a combined methodology integrating compositional, structural and quantitative analyses was developed.

Initial characterization of the materials was performed using X-ray fluorescence in order to determine the content of calcium oxide and other relevant oxides that define the theoretical maximum capture capacity. After carbonation experiments, X-ray diffraction analyses were conducted to identify phase transformations associated with the reaction between CO_2 and hydrated calcium compounds. Particular attention was paid to the disappearance of portlandite peaks and the increase in calcite reflections, in line with previous phase-identification approaches reported for carbonation studies (Bui et al., 2023).

To quantify carbonate formation, calcimetry using a Bernard calcimeter was performed on both untreated and carbonated samples. Calcimetry has been shown to be a reliable semi-quantitative tool for assessing carbonate content in mineral systems (Ledésert et al., 2009). The increase in $CaCO_3$ content was calculated from the volume of CO_2 released during acid digestion (Huntzinger et al., 2009). Based on reaction stoichiometry, the mass of CO_2 fixed per kilogram of material and the real capture percentage were determined. These values were compared with the theoretical maximum capture capacity derived from the initial composition, allowing calculation of the carbonation efficiency. The combination of structural and quantitative techniques proved essential to avoid misinterpretation of phase evolution in heterogeneous materials.

Carbonation experiments were carried out in a semi-industrial pilot plant, Figure 1, designed to validate HECO technology at relevant scale. The installation includes a gas supply system capable of providing controlled air and CO_2 streams, an electrical heating unit to reach operating temperature, a conical spouted bed reactor, solid feeding and discharge systems, gas cleaning units and an automated PLC-based control system.

The reactor consists of a lower truncated conical section connected to an upper cylindrical chamber. This configuration promotes cyclic particle movement resembling a fountain regime, enhancing gas–solid contact and minimizing channeling. The design allows stable operation in batch mode and ensures effective mixing of the solid bed.

Five materials were tested during two experimental campaigns. Three of them corresponded to construction waste residues supplied by an industrial client, while two additional materials with known carbonation potential were used as tracers for validation purposes. Experiments were conducted under conditions representative of industrial flue gas, with a gas mixture containing 20% CO_2 in air at approximately 120 °C and a residence time of 30 minutes. Each test was performed with approximately 5 kg of dry solid. Moisture content was adjusted to around 20% in order to favor carbonation kinetics while avoiding excessive agglomeration.

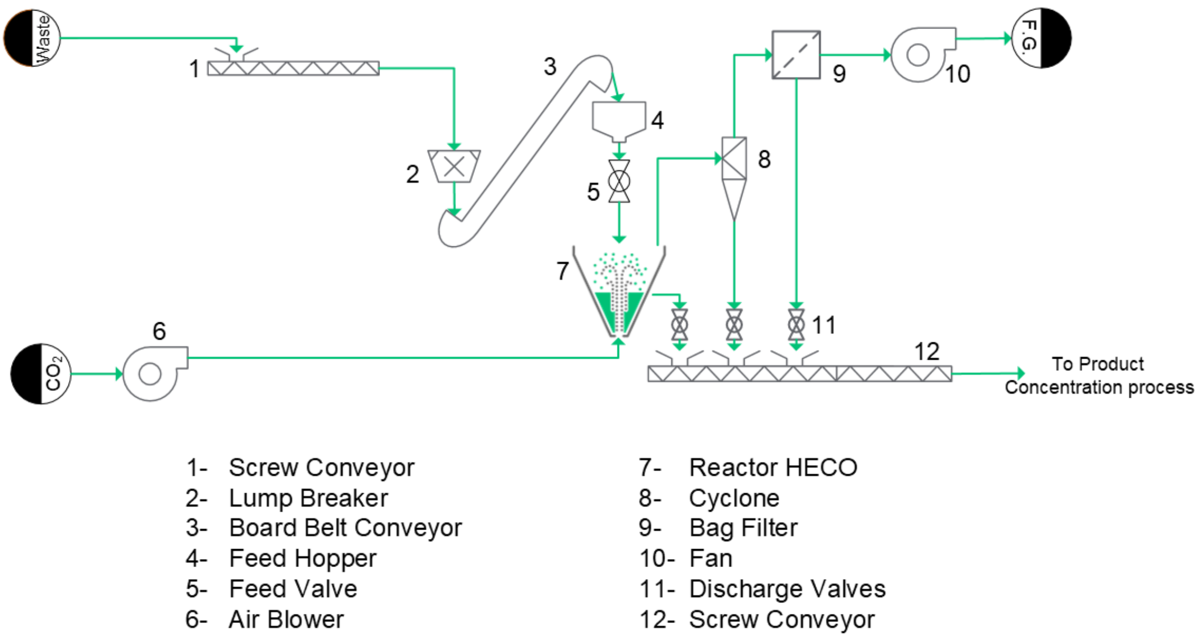

Figure 1 *Flowsheet diagram of the semi-industrial pilot plant used for the test*

Conclusions

The present study validates the technical feasibility of batch carbonation of construction waste using a semi-industrial conical spouted bed reactor based on HECO technology. A comprehensive methodology combining XRF, XRD and calcimetry allowed reliable quantification of carbonation performance in heterogeneous residues.

Calcium-rich construction wastes exhibited significant CO_2 sequestration capacity, reaching up to 149.71 g CO_2 per kilogram of material under realistic flue gas conditions. Process efficiency was strongly influenced by material composition and operational parameters, particularly moisture control and solid homogenization.

The results confirm the potential of HECO technology as a scalable solution for integrating CO_2 capture with waste valorization strategies. Semi-industrial validation represents a significant step toward increasing the technology readiness level and advancing its implementation in industrial environments.

References

Alonso, M., Rodríguez, N., Grasa, G., & Abanades, J. C. (2009). Modelling of a fluidized bed carbonator reactor to capture CO2 from a combustion flue gas. Chemical Engineering Science, 64(5), 883-891. https://doi.org/10.1016/j.ces.2008.10.044

Bui, H., Delattre, F., & Levacher, D. (2023). Experimental Methods to Evaluate the Carbonation Degree in Concrete—State of the Art Review. Applied Sciences, 13(4), Article 4. https://doi.org/10.3390/app13042533

Huntzinger, D. N., Gierke, J. S., Sutter, L. L., Kawatra, S. K., & Eisele, T. C. (2009). Mineral carbonation for carbon sequestration in cement kiln dust from waste piles. Journal of Hazardous Materials, 168(1), 31-37. https://doi.org/10.1016/j.jhazmat.2009.01.122

Ledésert, B., Hébert, R. L., Grall, C., Genter, A., Dezayes, C., Bartier, D., & Gérard, A. (2009). Calcimetry as a useful tool for a better knowledge of flow pathways in the Soultz-sous-Forêts Enhanced Geothermal System. Journal of Volcanology and Geothermal Research, 181(1), 106-114. https://doi.org/10.1016/j.jvolgeores.2009.01.001

Sanna, A., Uibu, M., Caramanna, G., Kuusik, R., & Maroto-Valer, M. M. (2014). A review of mineral carbonation technologies to sequester CO2. Chem. Soc. Rev., 43(23), 8049-8080. https://doi.org/10.1039/C4CS00035H