Air Pollution Control Residues for CO_2 Capture: an Integration of Calcium Looping and Accelerated Carbonation Technologies

Introduction

Air Pollution Control residues (APCr), produced in dry and semi-dry flue gas cleaning systems in sectors such as municipal solid waste incineration, glass, and ceramics manufacturing, constitute a significant hazardous waste stream due to their high content of soluble salts and leachable heavy metals [Dal Pozzo et al., 2023]. Despite these environmental constraints, APCr contain substantial amounts of calcium-bearing phases, including $Ca(OH)_2$, CaO, and other mixed calcium compounds, originating from the sorbents used during acid gas neutralization.
These calcium-rich phases provide APCr with inherent reactivity toward CO_2, making them suitable candidates for accelerated carbonation processes [Wehrung et al., 2024]. Exposure and reaction with CO_2 have been shown not only to enable CO_2 uptake but also to promote mineral transformations that can contribute to the stabilization of heavy metals within the residue matrix [Baciocchi et al., 2006; Pan et al., 2012]. Previous experimental investigations have further demonstrated that APCr are also capable of participating in repeated carbonation-calcination cycles under calcium looping (CaL) conditions, maintaining measurable CO_2 capture capacity over multiple cycles [Chianese et al., 2026].
This combination of intrinsic carbonation reactivity and the need for safe waste management positions APCr as promising alternative sorbents for both calcium looping and accelerated carbonation (AC), offering the potential to integrate CO_2 capture with residue stabilization and valorisation.

Methods and Theory

This study investigates an integrated process concept combining high-temperature calcium looping with low-temperature accelerated carbonation to simultaneously achieve CO_2 capture and stabilization of APCr. Accelerated carbonation at near-ambient conditions is known to promote heavy metal immobilization through mineral carbonation reactions; however, its effectiveness is limited by single-pass operation, which typically restricts CO_2 uptake to approximately 10-20 wt.% relative to the initial APCr mass [Chen et al., 2025]. In contrast, calcium looping enables repeated carbonation-calcination cycles, allowing progressive and cumulative CO_2 capture while generating a concentrated CO_2 stream suitable for downstream utilization or storage.
In the proposed system, APCr are directly used as sorbents in a dual fluidized bed CaL configuration. During operation, carbonation occurs at approximately 700°C, where reactive calcium phases react with CO_2 to form $CaCO_3$. The sorbent is subsequently regenerated at 900-950°C in the calciner, releasing a concentrated CO_2 stream and restoring the reactive CaO phase for further cycling.
Thermogravimetric analysis was conducted over 20 carbonation-calcination cycles to characterize the cyclic capture behaviour of APCr. The results, shown in Figure 1-(a), reveal a distinctive performance evolution compared to conventional limestone. Rather than exhibiting an immediate and continuous loss of capacity, APCr show an initial increase in CO_2 uptake during the first cycles, followed by gradual deactivation. Despite variability between samples, the cumulative CO_2 uptake achieved through cyclic operation exceeds that attainable via single-pass accelerated carbonation of the same material, confirming the effective utilization of reactive calcium phases during CaL operation.
Given that the environmental classification of APCr is primarily governed by leaching behaviour, the study places particular emphasis on evaluating contaminant stabilization. Leaching tests targeting key heavy metals, including Cu, Pb, and Zn, were conducted on samples before and after CaL treatment to assess the impact of repeated high-temperature cycling, phase transformation, and structural evolution on contaminant mobility.
A flexible, decision-oriented process design strategy was therefore adopted, whereby experimental leaching results served as the key criterion for defining the final treatment configuration. Two alternative process layouts were assessed. When the dry carbonation of CaL alone achieved the required stabilization targets, a simplified scheme comprising CaL with optional washing for chloride removal was selected (Figure 1-(b)). Conversely, if leaching limits were not met, a downstream accelerated carbonation stage was incorporated to further enhance contaminant immobilization (Figure 1-(c)). This

secondary carbonation stage operates under thin-film conditions and utilizes the concentrated CO_2 stream produced in the calciner to further promote carbonation reactions and enhance contaminant immobilization.

To evaluate the feasibility of the selected configurations at industrial scale, detailed mass and energy balances were developed using Aspen Plus process modelling. Preliminary equipment sizing was performed for key system components, and a techno-economic assessment was conducted to compare the integrated CaL-AC process with conventional APCr management routes, including hazardous landfill disposal and salt mine backfilling, in order to identify performance trade-offs and the operational conditions under which APCr utilization within CaL systems becomes technically and economically advantageous.

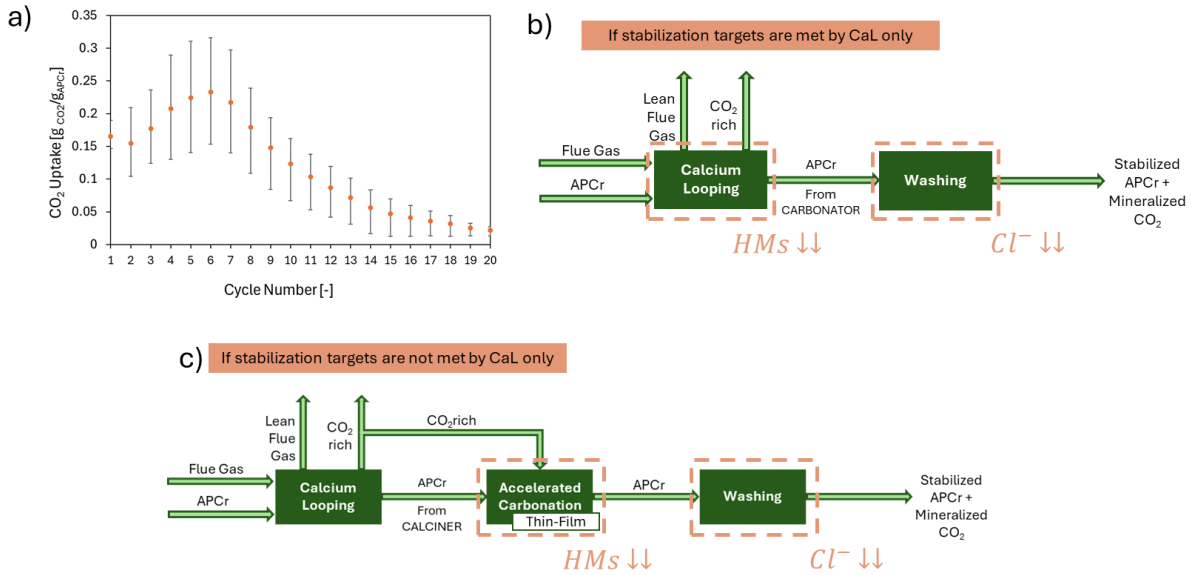

Figure 1 *Cyclic CO_2 uptake of APCr over multiple carbonation-calcination cycles (error bars represent experimental variability); Process configurations: b) CaL with washing; c) CaL combined with accelerated carbonation and washing. Dashed boxes denote stages dedicated to heavy metal (HM) and chloride (Cl^-) reduction.*

Conclusions

This work assesses the feasibility of using Air Pollution Control residues as sorbents in calcium looping systems, allowing cyclic CO_2 capture while promoting partial stabilization of hazardous components. When stabilization targets are not fully achieved, additional treatments such as accelerated carbonation can be selectively implemented to enhance contaminant immobilization. By integrating calcium looping with accelerated carbonation, the proposed approach provides a scalable solution that combines CO_2 capture and mineralization with hazardous waste treatment and potential material valorisation, contributing to more resource-efficient and integrated carbon and waste management strategies.

References

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