New Frontiers in Harnessing Earth-Abundant Slags for Resource Recovery and Managing CO_2 Emissions

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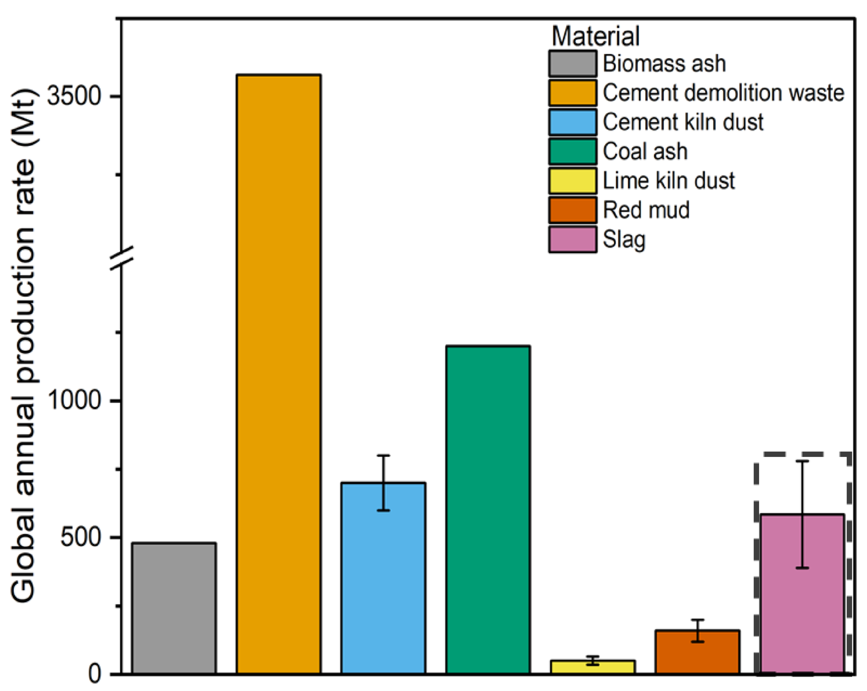
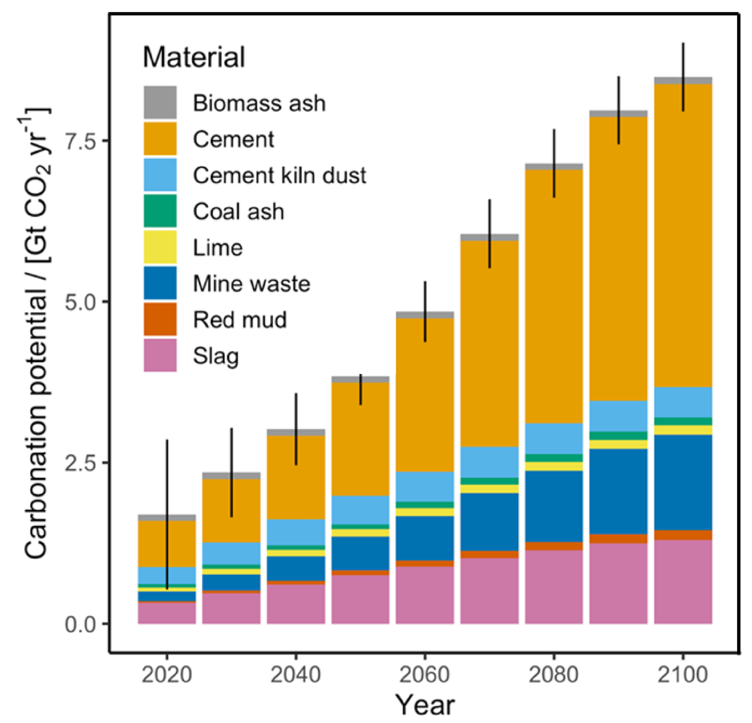
Introduction and Motivation

- Hard-to-abate sectors contribute ~40% of annual greenhouse gas emissions.
- Iron and Steel industries generate millions of tons of Ca/Mg-rich slags annually.
- These alkaline residues have high carbonation potential but are often underutilized and usually landfilled, leading to environmental concerns.
- Slag valorization offers dual benefits:
  1. Durable CO_2 storage via mineralization
  2. Resource recovery and generation of value-added products

Alkaline industrial residues are an abundant and underutilized resource for durable CO_2 storage





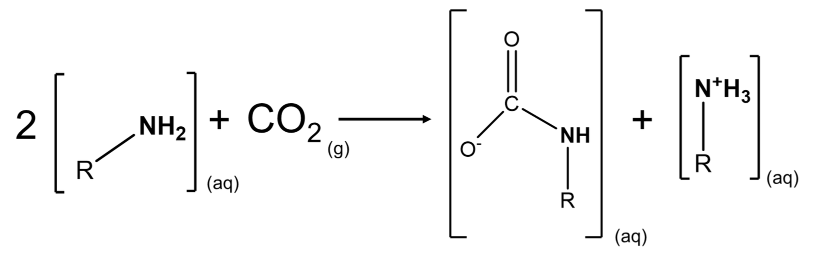
Objective

The objective of this study is to **develop a sustainable pathway** that captures industrial CO_2 emissions using amine-based solvents and mineralizes alkaline residues into stable carbonate-bearing solids.

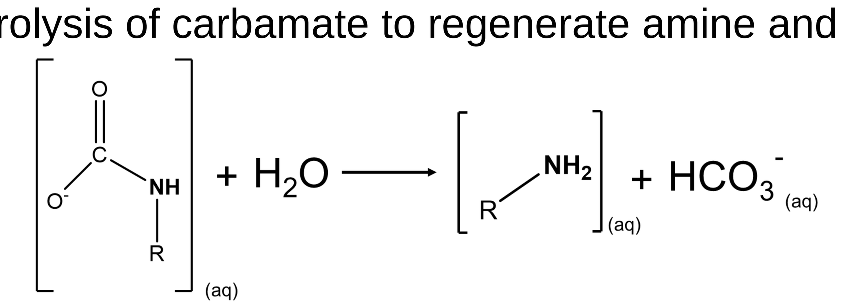
This process not only produces high-performance supplementary cementitious materials (SCMs) but also enables the recovery of valuable metals, such as Fe, Al, and Mn, promoting **industrial efficiency and resource utilization goals**.

Reactive CO_2 Capture and Mineralization

Reaction 1: Formation of carbamate and zwitterion on reaction with CO_2



Reaction 2: Hydrolysis of carbamate to regenerate amine and form bicarbonate



Reaction 3: Deprotonation of bicarbonate to form carbonate ions

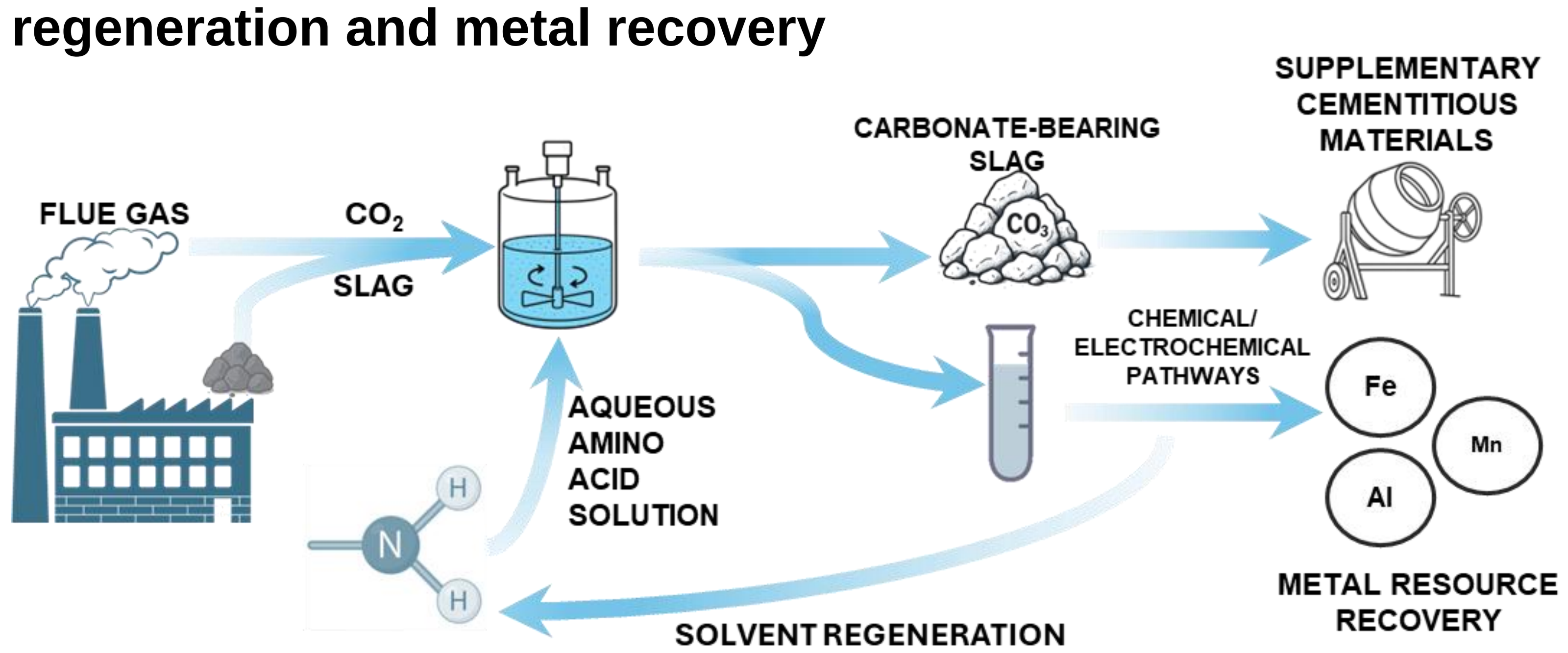
$$HCO_3^-{}_{(aq)} \longrightarrow CO_3^{2-}{}_{(aq)} + H^+{}_{(aq)}$$

Reaction 4: Carbonate formation via interaction of carbonate ions with metal cations

$$Ca^{2+}/Mg^{2+}{}_{(aq)}\ \text{(from slag)} + CO_3^{2-}{}_{(aq)} \longrightarrow CaCO_3/MgCO_3\ {}_{(s)}$$

Approach

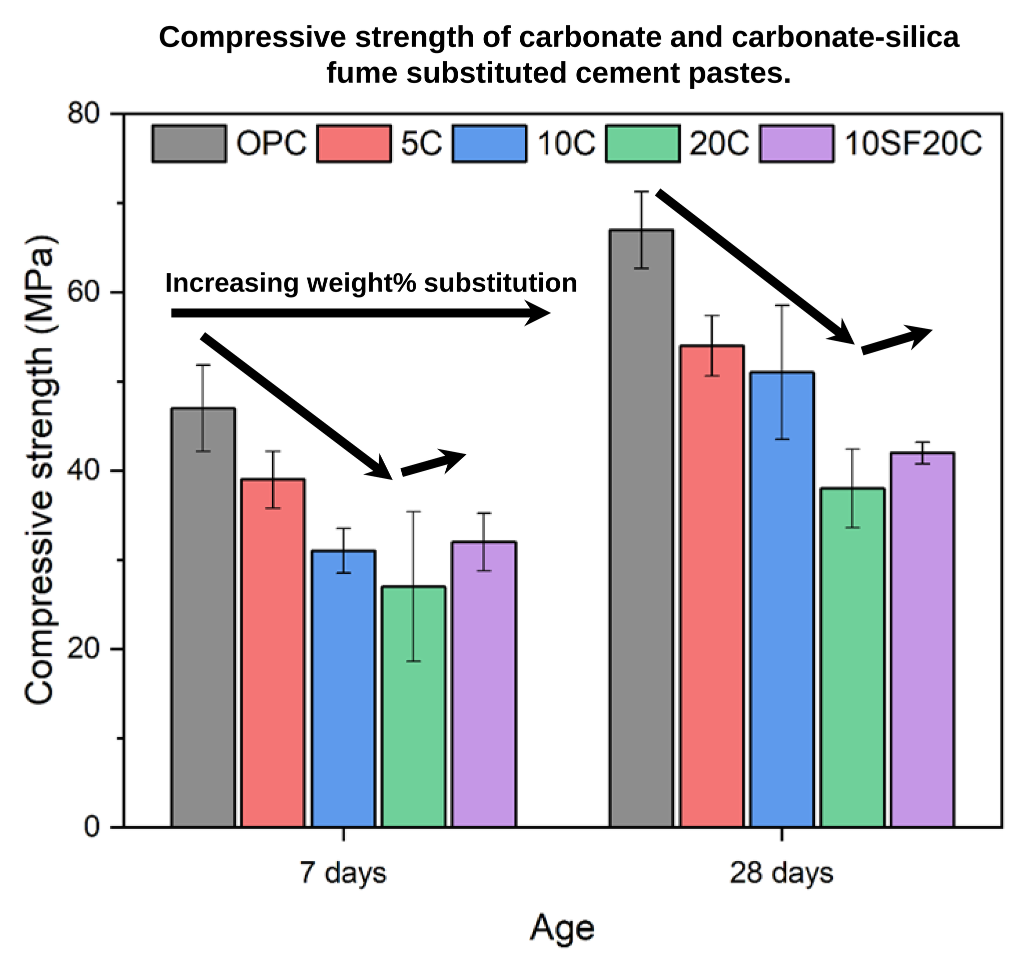
Direct integrated approach for CO_2 capture and mineralization to produce mixed carbonates, with simultaneous solvent regeneration and metal recovery



Key Results

Impact of carbonate and silica co-substitution on compressive strength of cement composites

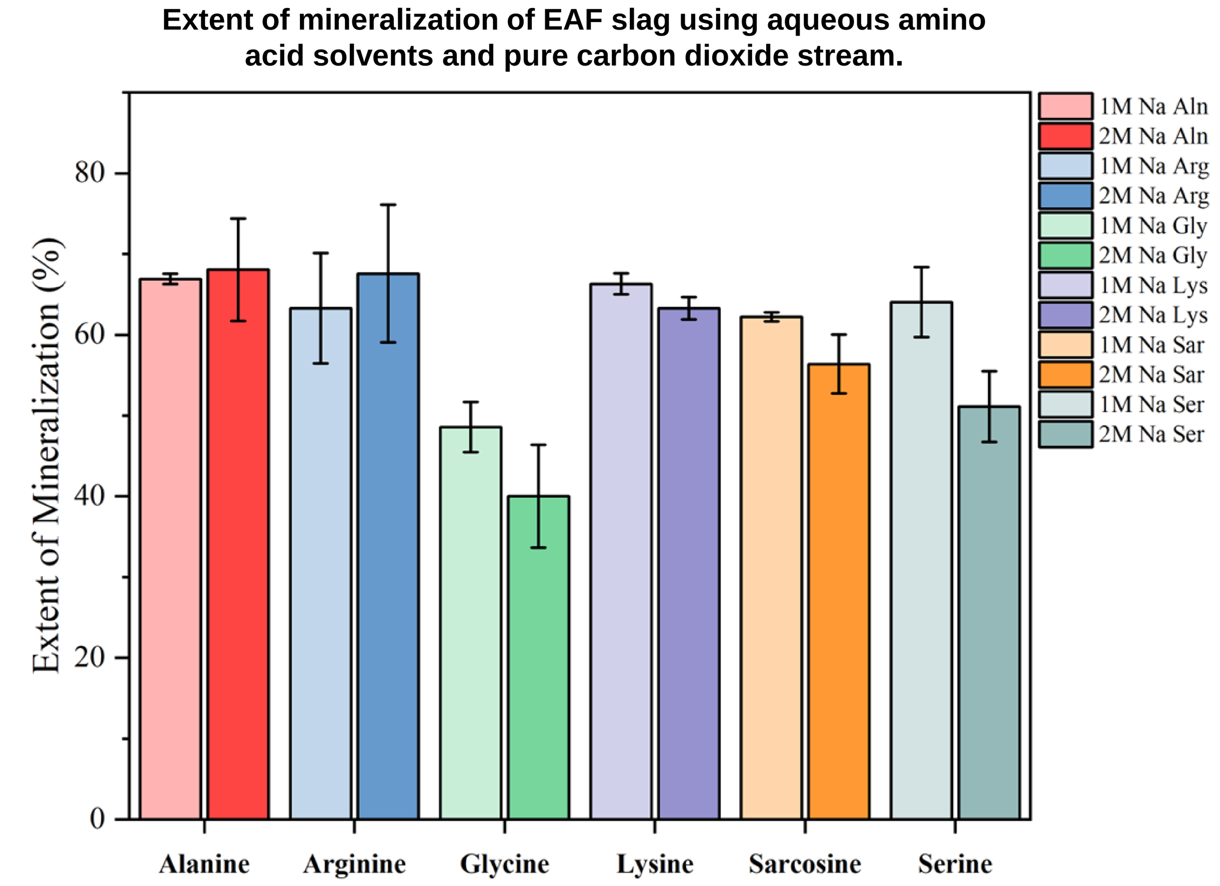
Compressive strength of carbonate and carbonate-silica fume substituted cement pastes.



Incorporating a reactive silica phase counteracts the dilution effect of comparatively inert carbonates, allowing for higher substitution levels and improved strength recovery.

Valorization of slag as a multi-functional supplementary cementitious material and a carbon sink

Extent of mineralization of EAF slag using aqueous amino acid solvents and pure carbon dioxide stream.

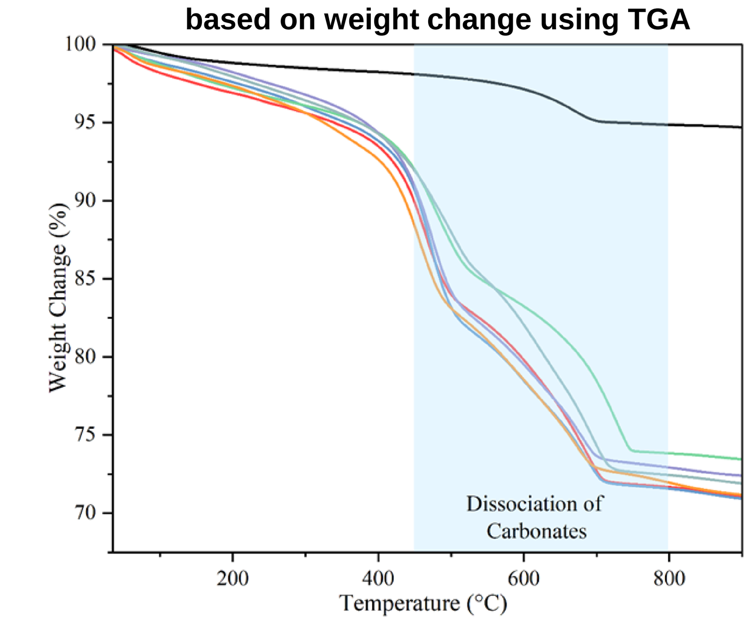


XRF major elemental concentrations in EAF slag

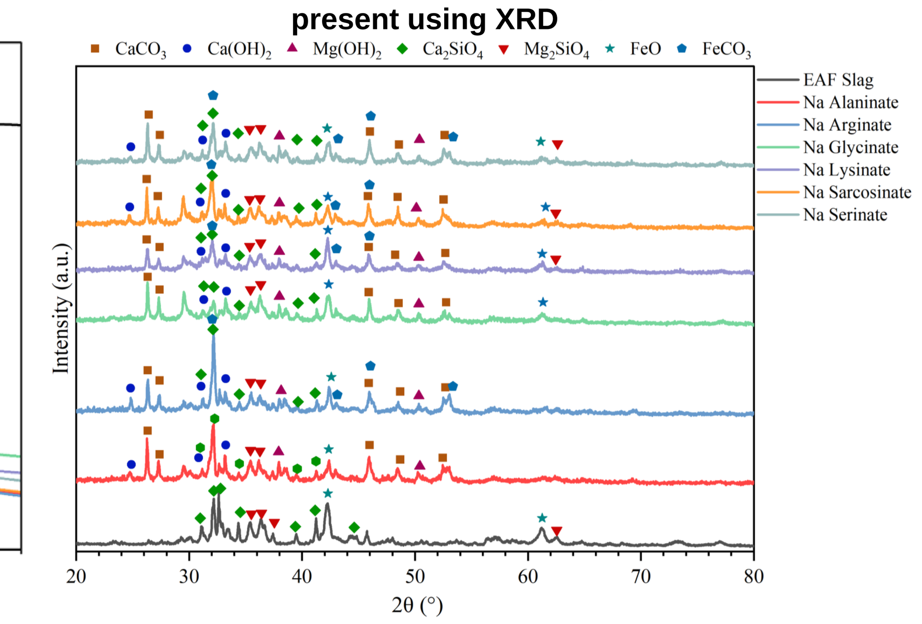
Major Elements	Wt% oxides
CaO	33.5
FeO*	23
SiO_2	15.69
MgO	12.47
Al_2O_3	8.06
MnO	4.884
TiO_2	0.484
P_2O_5	0.383
Na_2O	0.11
K_2O	0.07

Key Results

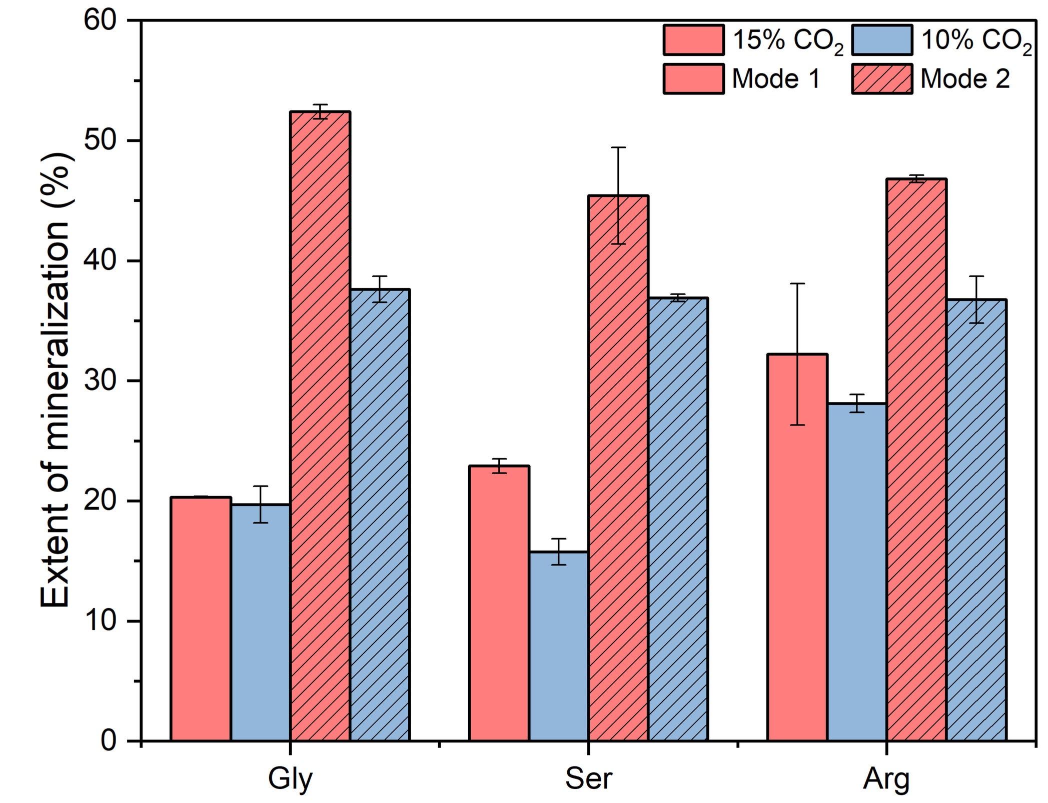
Evidence of calcium carbonate formation based on weight change using TGA

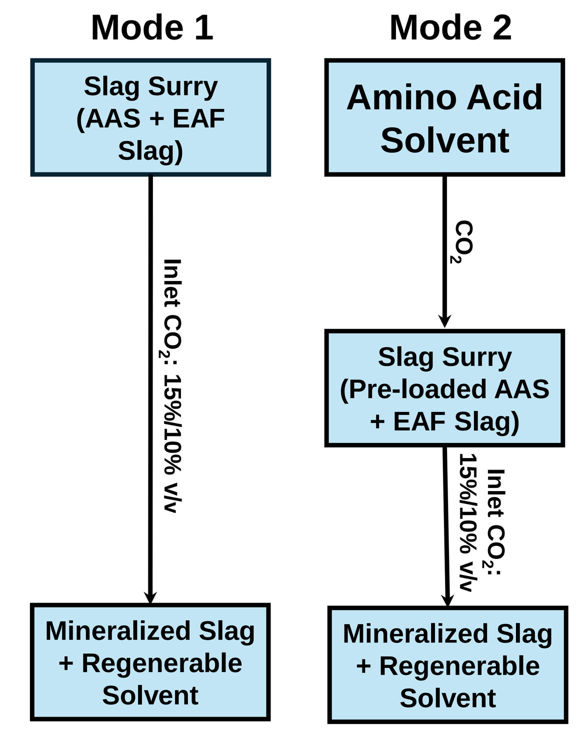


Evidence of calcium carbonate phases present using XRD

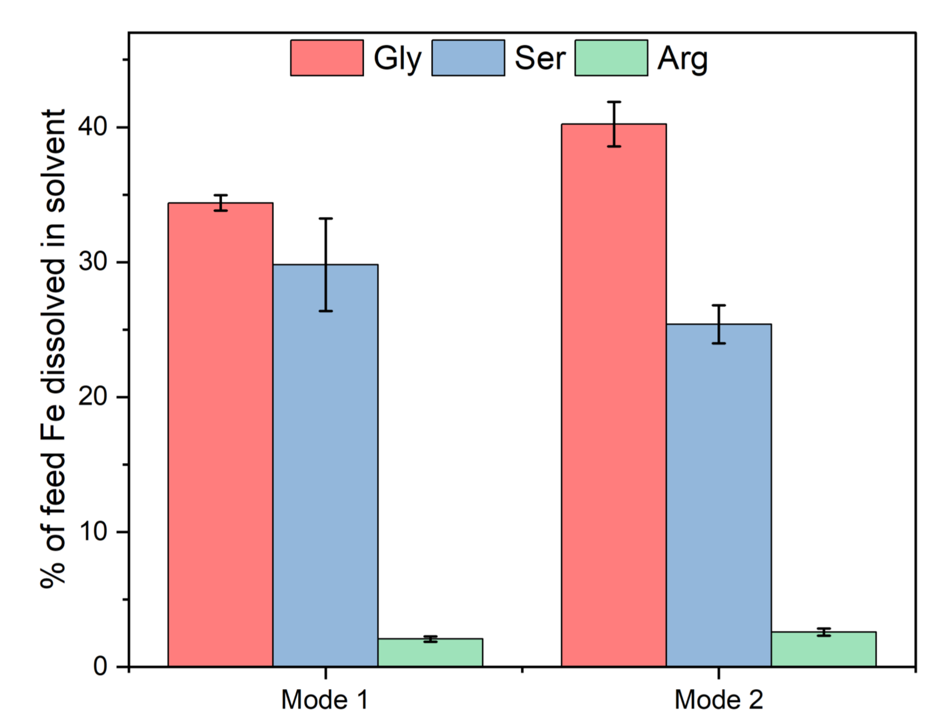


Extent of mineralization of EAF slag using aqueous amino acid solvents and dilute carbon dioxide stream.





Metal recovery potential through integrated mineralization approach



Conclusions

- ❑ The reactive CO_2 capture and mineralization process permanently stores CO_2 in stable carbonates while producing reactive SCMs and enabling valuable metal recovery from slag.
- ❑ Carbon mineralization efficiency exceeding 70% is achieved, demonstrating strong potential for CO_2 management
- ❑ Fe leaching from slag ~ 40% highlights opportunities for economic metal recovery.