Theme: Exploring the Use of Mine Tailings in Cementitious Materials

Towards Phosphogypsum & Red Mud-based Low-Carbon Cement Composites

Presenter: Dr. Muhammad Nasir

Postdoctoral Fellow, FCI

PI: Prof. Bassam Dally

Chair, FCI

Production of PG and RM

Environmental burden and resource potential of PG and RM

ORIGIN AND PRODUCTION RATE

- Phosphogypsum (PG) is a by-product generated during the production of phosphoric acid from phosphate rock. 7 billion tons of PG have been generated worldwide, with a current production rate of 200–280 million tons per annum. 13 million tons/y in KSA.

- Red Mud (RM) is a by-product produced during alumina extraction from bauxite in the Bayer process. 4.6 billion tons of RM have been generated worldwide, with a current production rate of 120-180 million tons. 2 million tons/y in KSA.

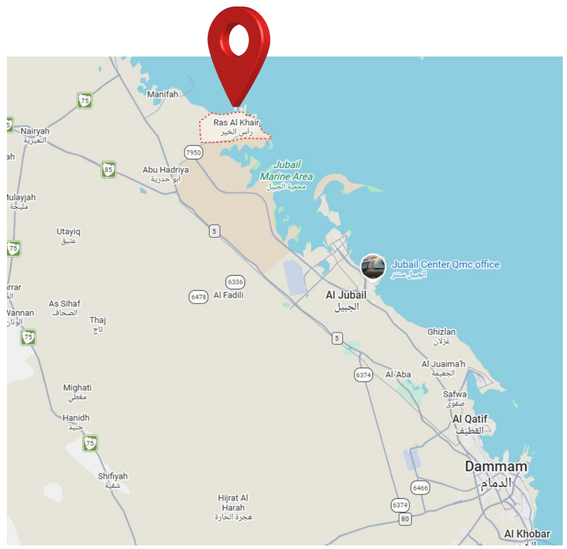
VALORISATION RATE

- Only 14% of the PG generated annually is currently utilized.

- Only 2–5% of the RM generated annually is currently utilized.

- Despite the massive production of PG and RM worldwide, less than 15% is valorized, highlighting the urgent need for innovative solutions for their sustainable management.

MA'ADEN معادن
Saudi Arabian Mining Company شركة التعدين العربية السعودية



ENVIRONMENTAL CHALLENGES & ECONOMIC LOSSES

- Large land occupation.

- Soil and groundwater contamination.

- Waste of valuable components, e.g., REEs.



OPPORTUNITY

- Pre-treatment of the RM and PG (radioactivity)

- Neutralization of the acidity of PG

- Immobilization of impurities

- Recovery of valuable elements

- Reduced waste storage

- Low-carbon cement composites










Jovičević-Klug, Matic, et al. "Green steel from red mud through climate-neutral hydrogen plasma reduction." Nature 625.7996 (2024): 703-709.

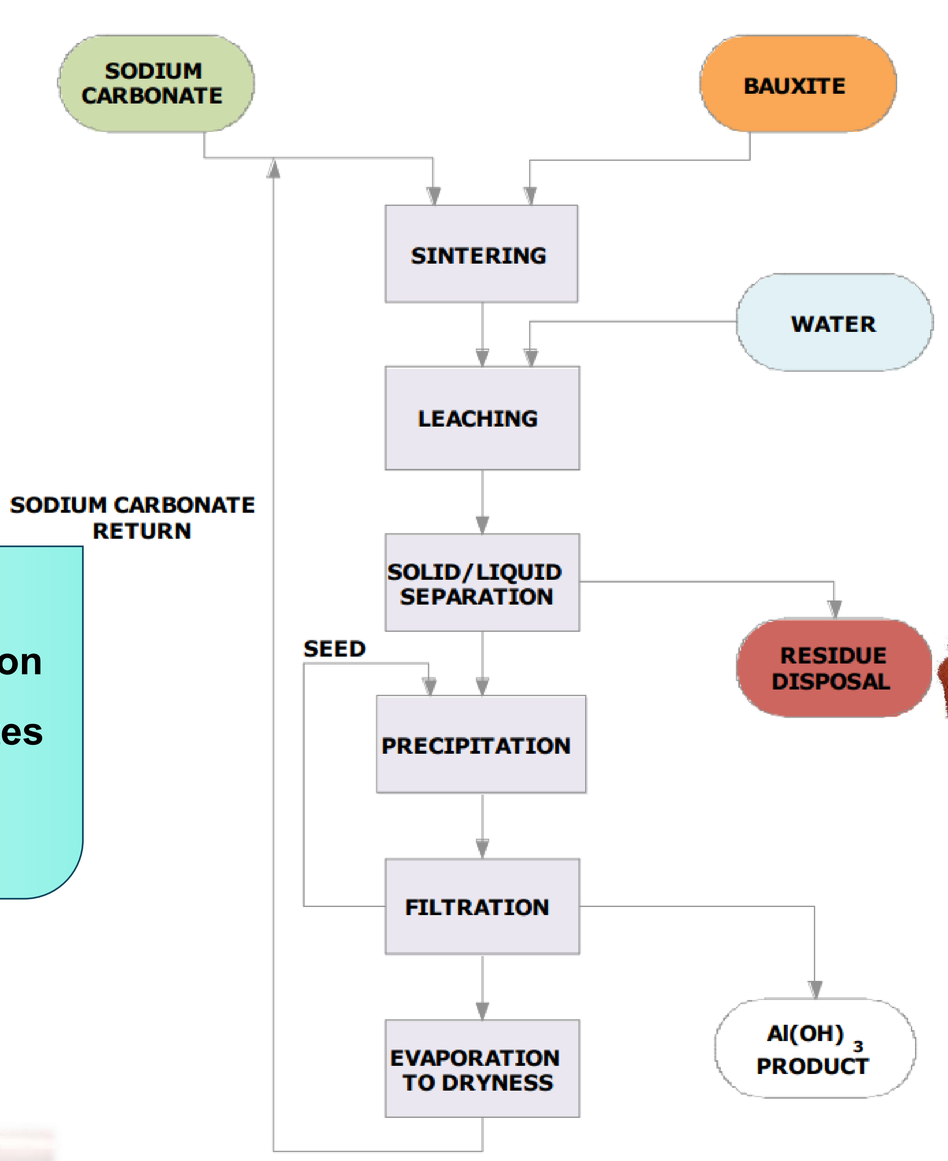
Ujaczki, Éva, et al. "Re-using bauxite residues: benefits beyond (critical raw) material recovery." *Journal of Chemical Technology & Biotechnology* 93.9 (2018): 2498-2510.

Generation of RM during the production of Aluminum from Bauxite

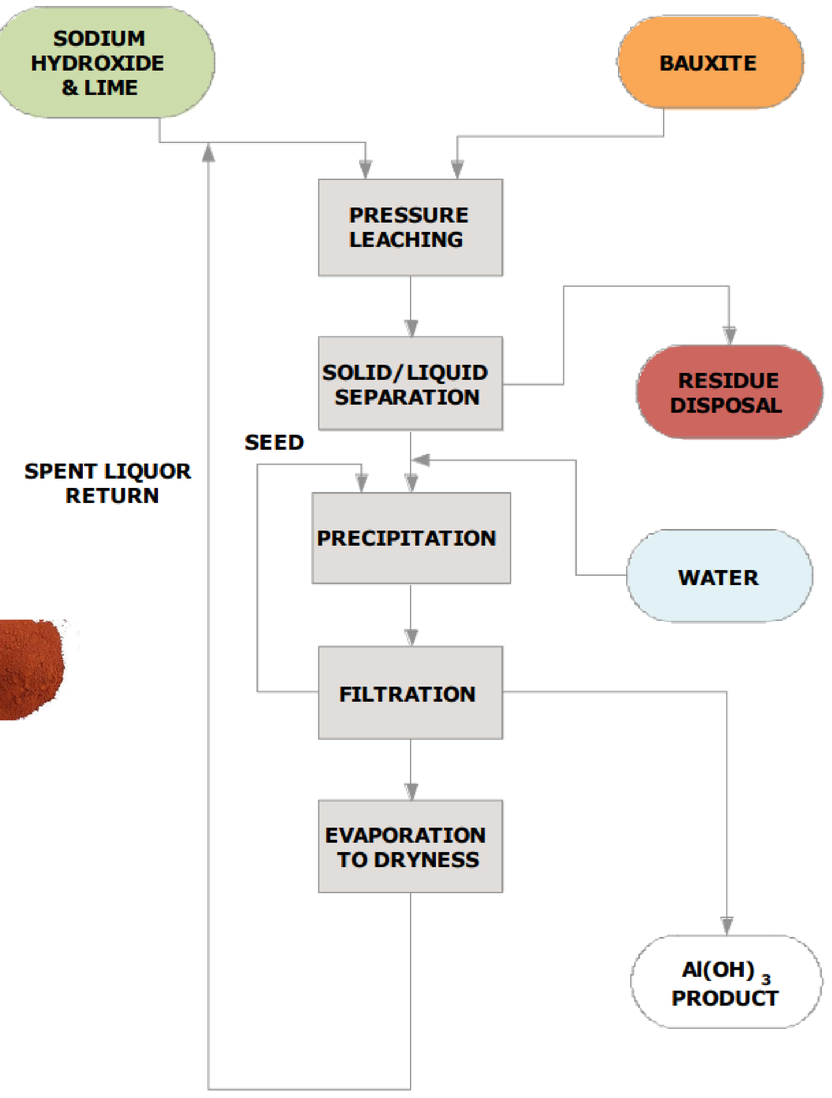
The process of each ton of bauxite ore generates ~1 ton of RM.

Opportunity





SINTER PROCESS (BAYER 1888)



LEACH PROCESS (BAYER 1892)
("The Bayer Process")

Flow diagrams for the two processes patented by Bayer.

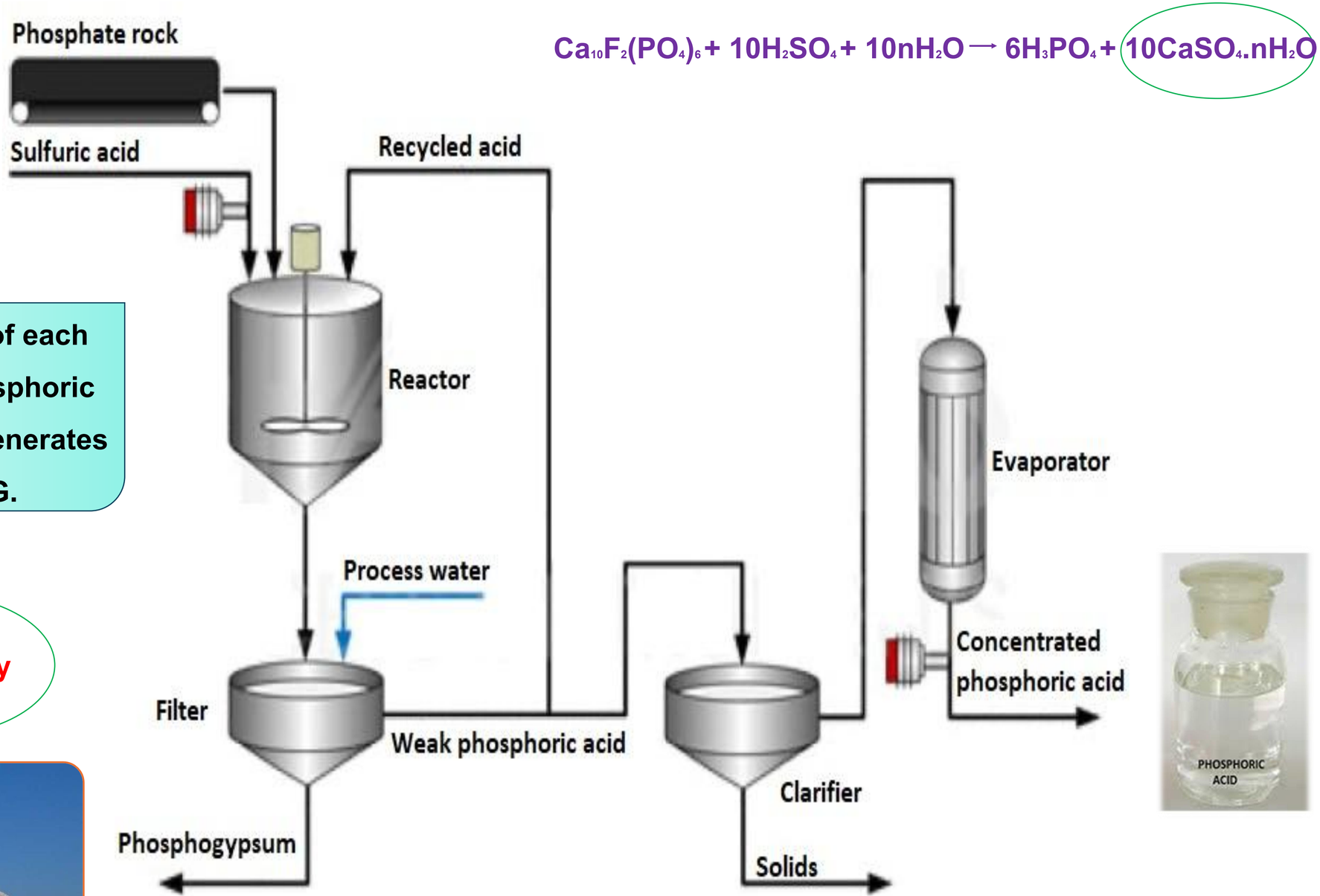
Generation of PG during the production of Phosphoric Acid from Phosphate Rock

$$Ca_{10}F_2(PO_4)_6 + 10H_2SO_4 + 10nH_2O \rightarrow 6H_3PO_4 + 10CaSO_4.nH_2O + 2HF$$

The production of each ton of crude phosphoric acid (28% P_2O_5) generates **5 tons** of PG.

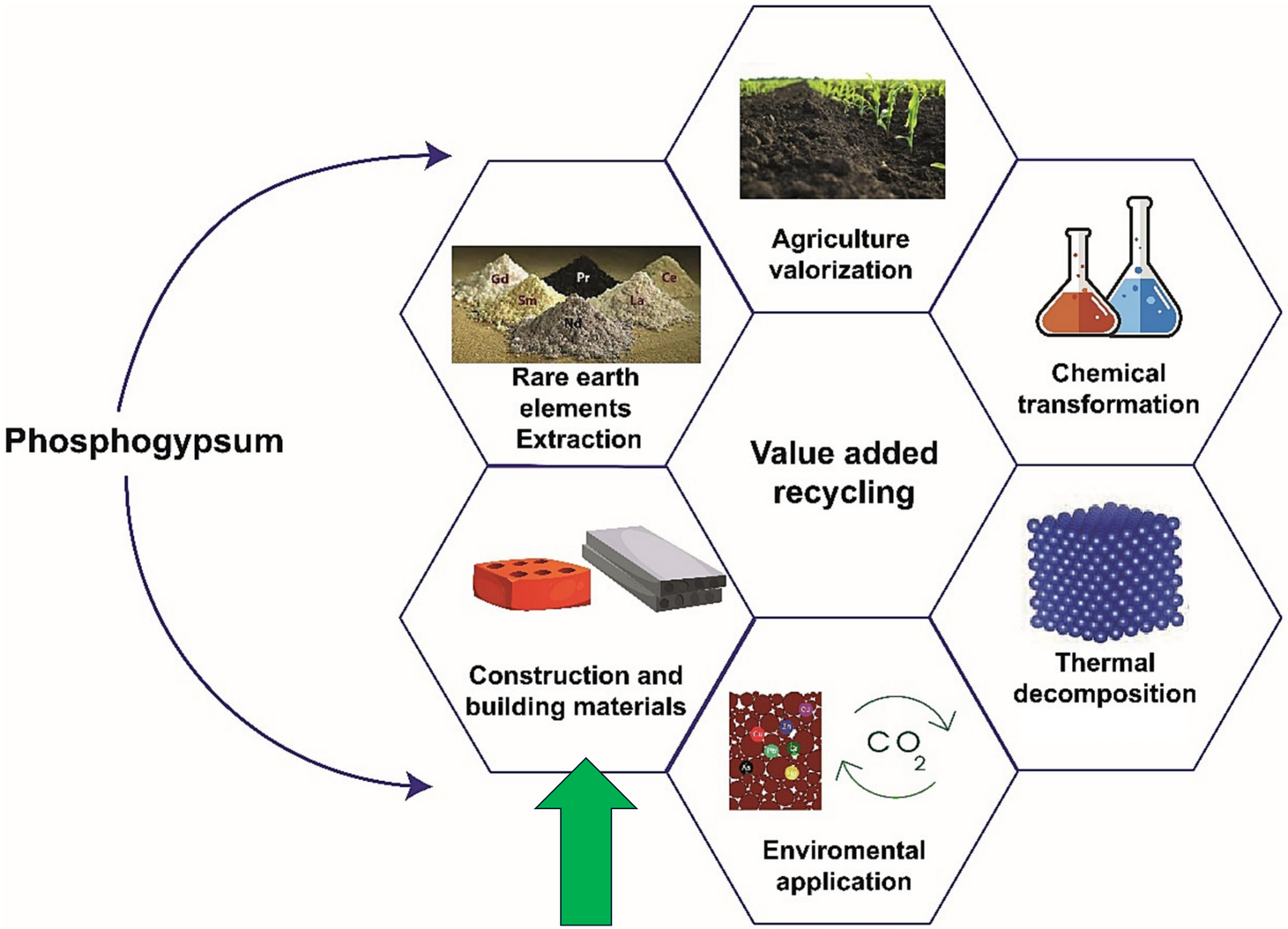
Opportunity



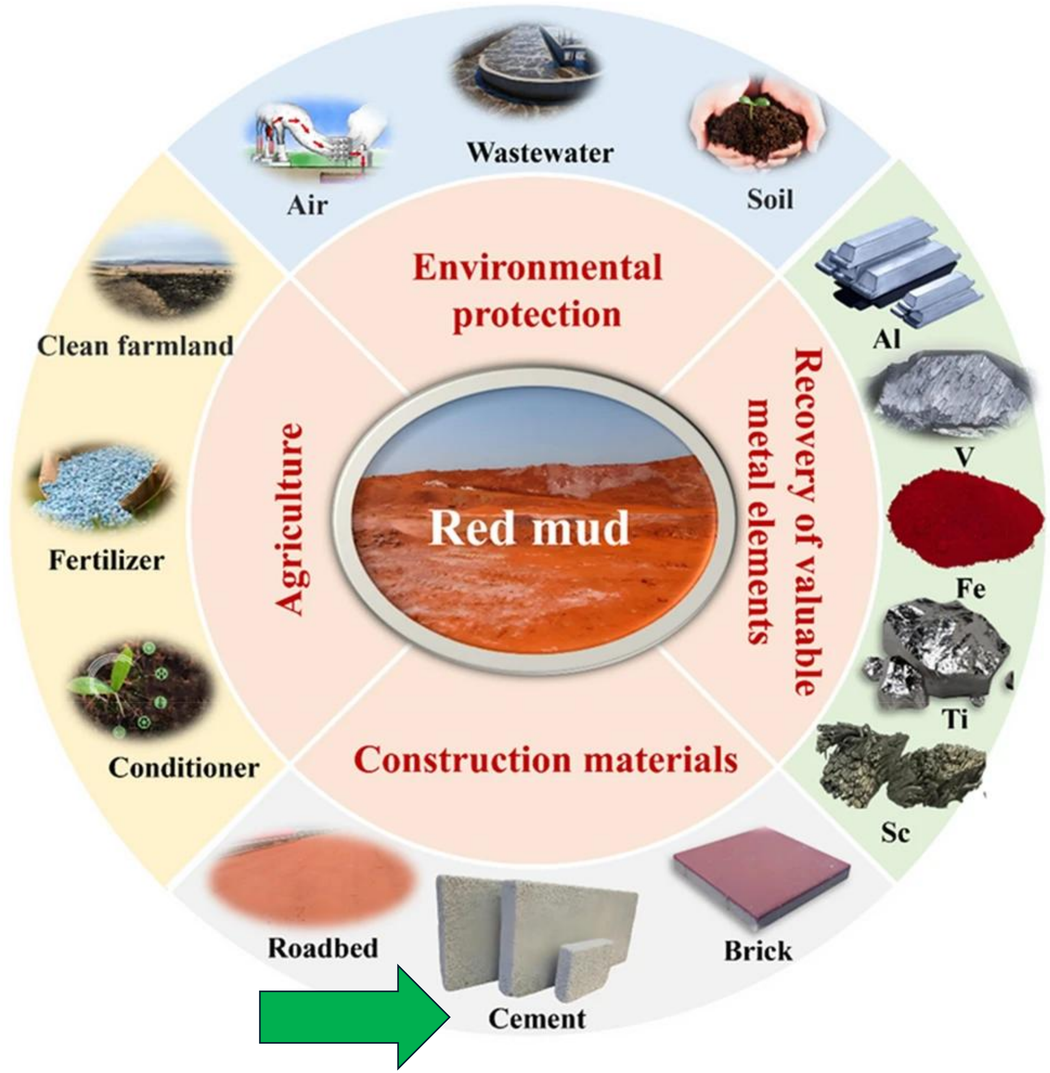


Schematic representation of the wet process phosphoric acid production.

Potential valorization pathways of PG and RM



Potential valorization pathways of PG.



Potential valorization pathways of RM.

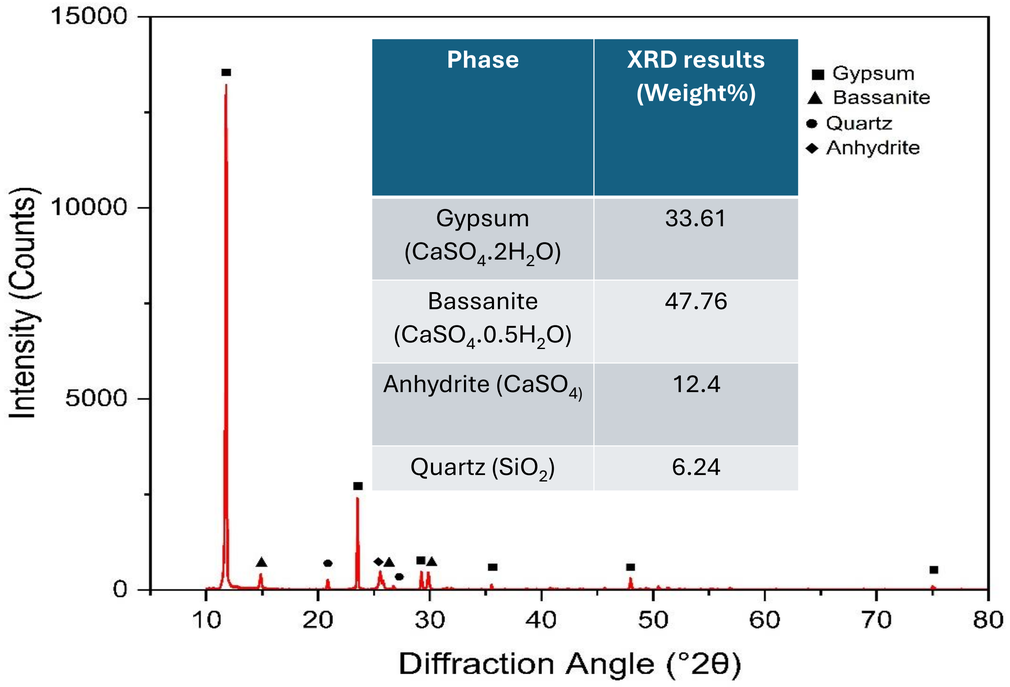
Akfas, Fatima, et al. "Exploring the potential reuse of phosphogypsum: a waste or a resource?." *Science of the total environment* 908 (2024): 168196.

He, Xin, et al. "Green Process for Red Mud Utilization: Iron Recovery and Cement Precursor Synthesis." *Journal of Sustainable Metallurgy* 11.3 (2025): 3169-3185.

Characterization of PG & RM

Characterization of PG

Analysis	Saudi Arabia	Algeria	India	Morocco
SO_3	46.5	40.90	43.21	42.9
CaO	33.8	31.18	31.09	30.5
P_2O_5	1.01	0.87	0.47	0.5
SiO_2	6.77	0.88	0.29	9.5
Na_2O	0.821	1.32	0.29	-
MgO	0.184	0.06	1.31	0.3
Fe_2O_3	0.04	0.03	-	0.9
Al_2O_3	0.131	0.1	0.54	2.8

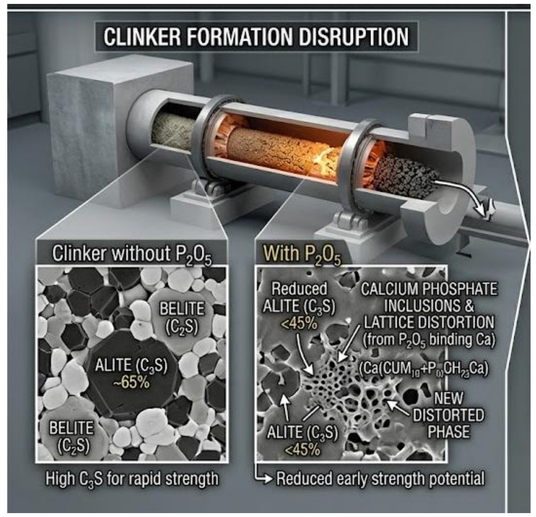


Phase	XRD results (Weight%)
Gypsum ($CaSO_4.2H_2O$)	33.61
Bassanite ($CaSO_4.0.5H_2O$)	47.76
Anhydrite ($CaSO_{4)}$	12.4
Quartz (SiO_2)	6.24

- PG has a **high SO_3** concentration when analyzed via X-ray Fluorescence (XRF) because its primary chemical component is **calcium sulfate dihydrate** ($CaSO_4 \cdot 2H_2O$), as evident by X-ray Diffraction (XRD)

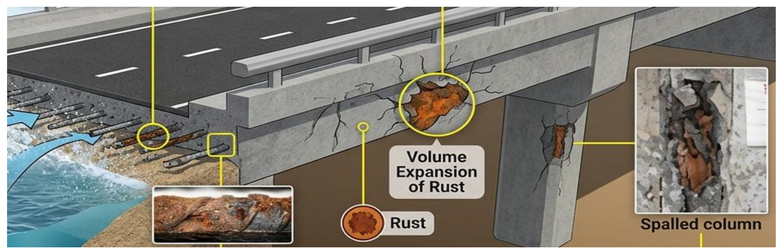


- PG shows **P_2O_5** in XRF because it is an unavoidable byproduct of the wet-process phosphoric acid industry.



[C_3S Hydration + P_2O_5 Interactions] → Delayed Reactions → Matrix Weakening → Early Strength Loss

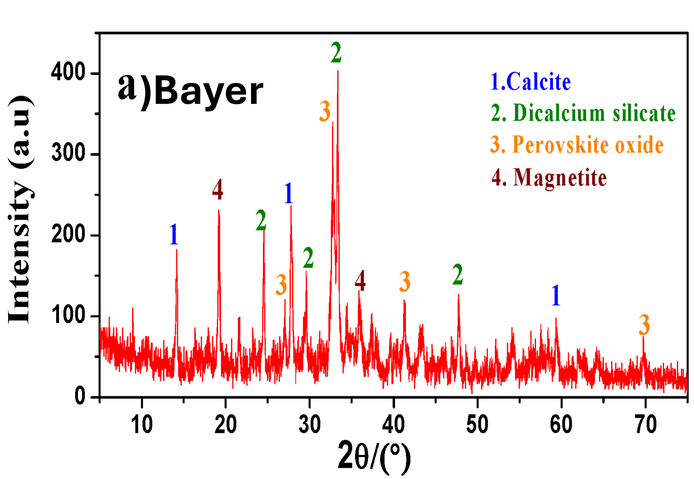
- PG has **low pH of ~2**.

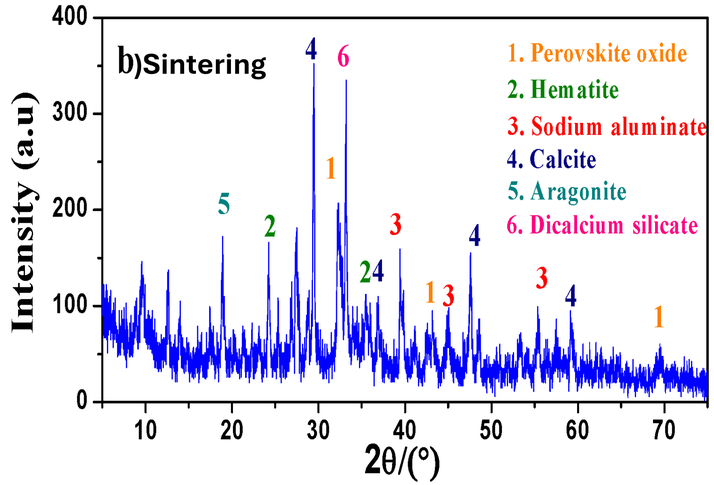


Qin et al. "Resource utilization and development of phosphogypsum-based materials in civil engineering."J. of Cleaner Prod. (2023)

Characterization of RM

Place	Production process	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	TiO_2	K_2O	MgO	Loss	Total
Saudi	Bayer	16.8	24	21.9	7.2	7.7	7.8	0.07	-	-	85.4
ShanDong	Bayer	22.3	18.32	37.11	1.57	5.2	2.87	0.17	0.1	11.4	99.04
ShanXi	Bayer	17.44	23.6	4.18	20.24	8.57	6.94	–	–	11.51	92.48
GuiZhou	Sintering	25.9	8.5	5	38.4	3.1	4.4	0.2	1.5	11.1	98.1
ShanXi	Sintering	21.43	8.22	8.12	46.8	2.6	2.9	0.2	2.03	8	100.3



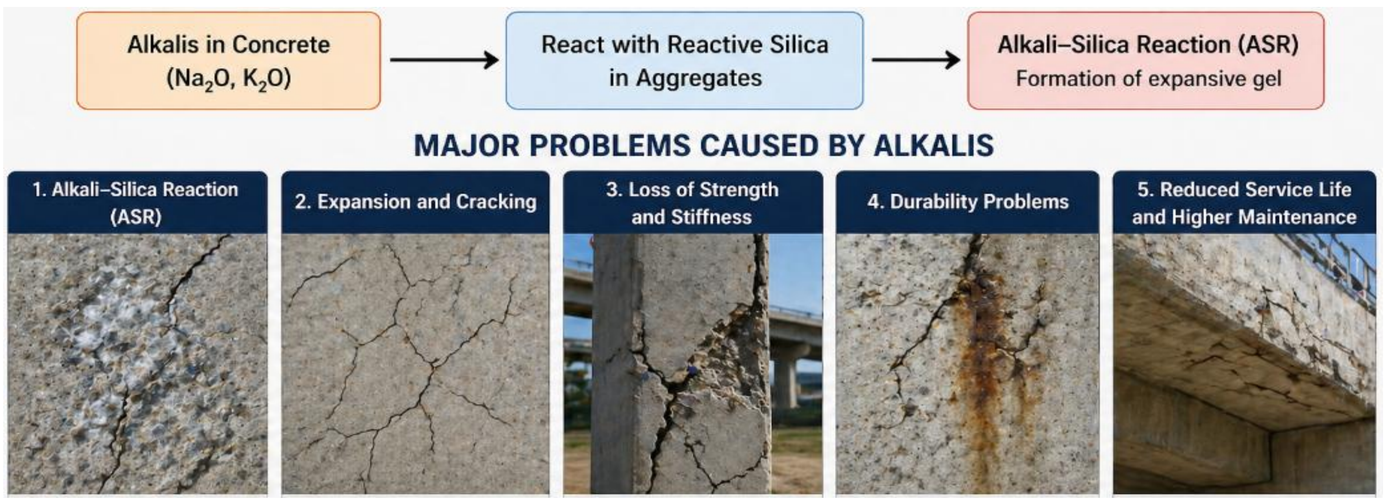


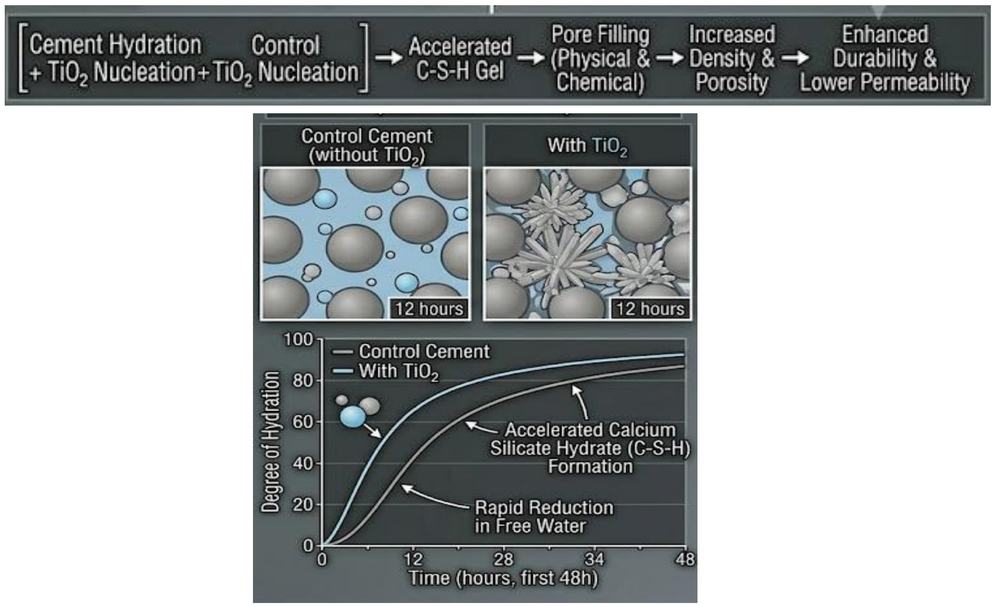
- **The Bayer process** uses strong alkali NaOH to dissolve high-aluminum and high-iron

  → **alumina, iron oxide, and alkali content**.

- **The sintering process** uses the combined process to address insoluble high-alumina, high-silicon, low-iron

  → **high CaO content, low alkali, and iron oxide**.



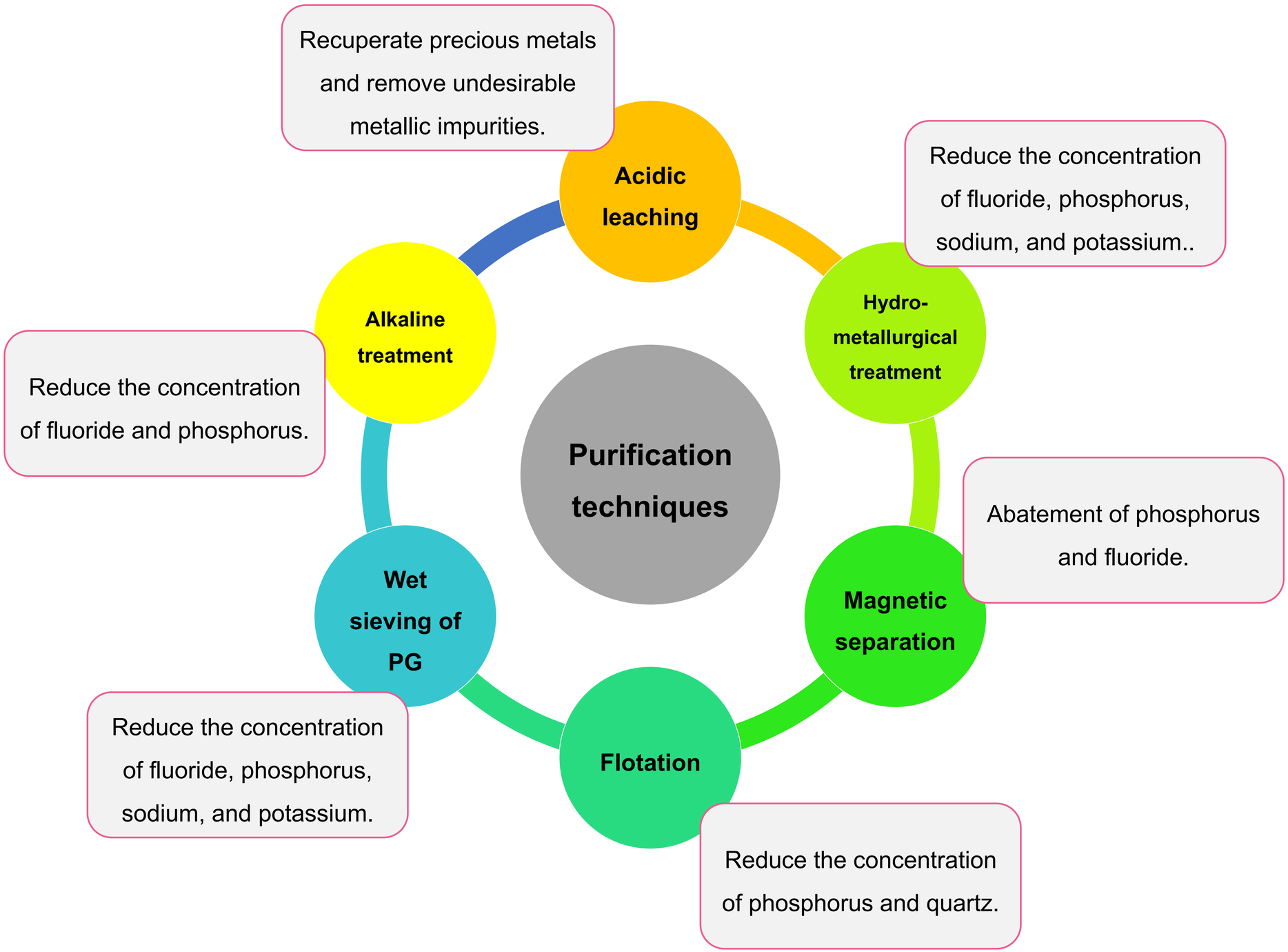


Wang & Liu. "Physical and Chemical Properties of Sintering Red Mud and Bayer Red Mud and the Implications for Beneficial Utilization.“Materials”. (2012)

Treatment & Performance of PG & RM in Cement Composites



Treatment of PG



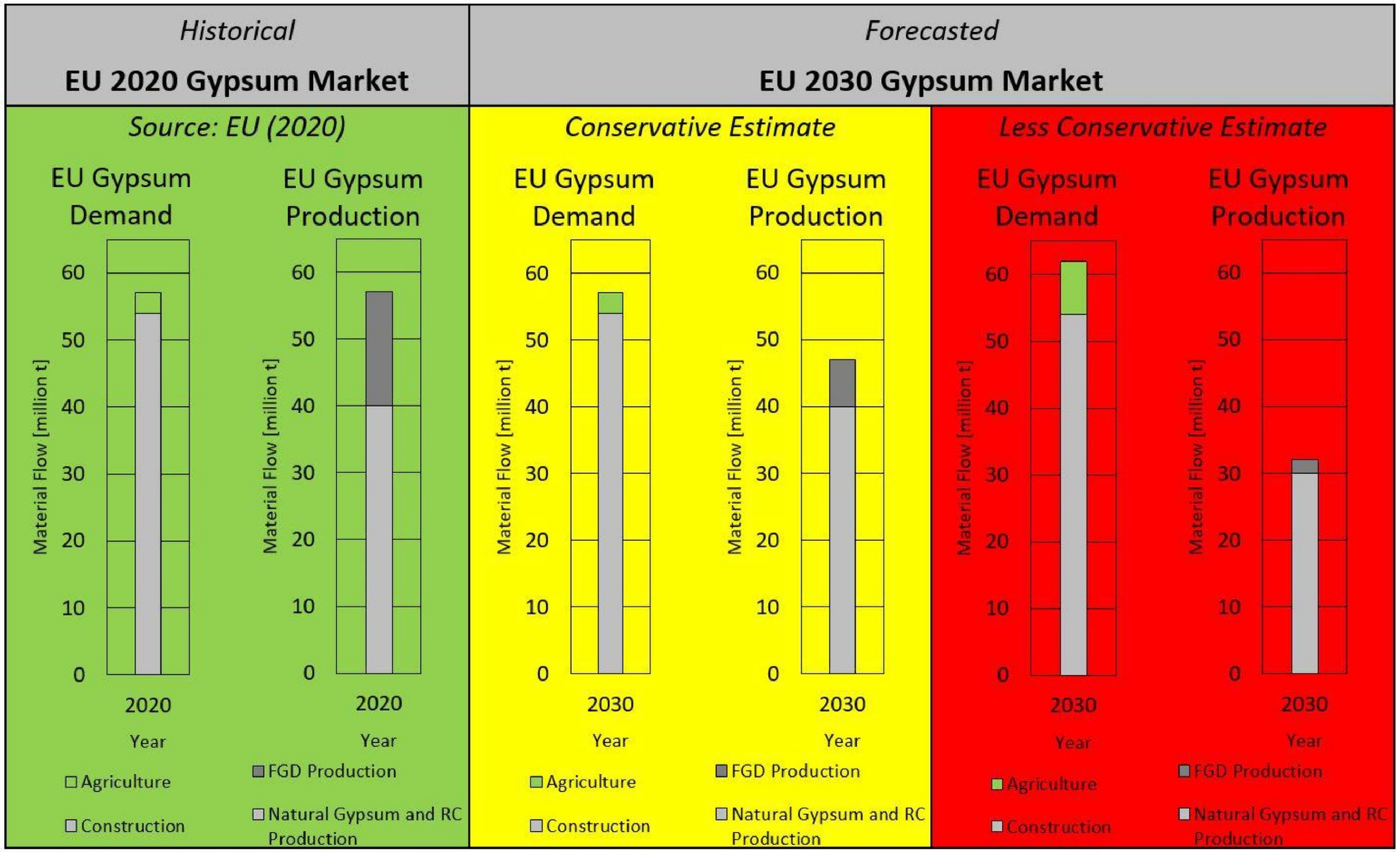
PG is highly acidic, ~ **pH 2.0.** This acidity is primarily due to residual traces of phosphoric and hydrofluoric acids from its production process. However, **neutralized or lime-treated** variants can shift to an alkaline **pH of 7 to 12**.

Wang & Liu "Applications of red mud as an environmental remediation material: A review."J. of Hazardous Mat. (2021)

Application of PG

Supply risk

The forecasted studies estimate that the gap between the demand and supply of gypsum will reach 10 to 30 million tons per year in 2030.

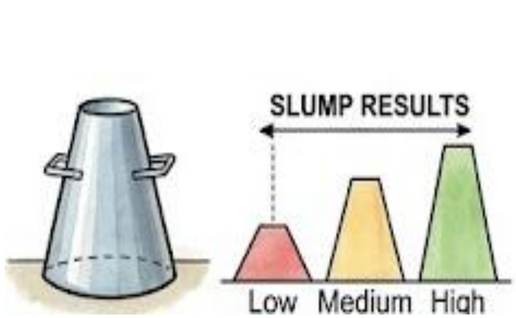


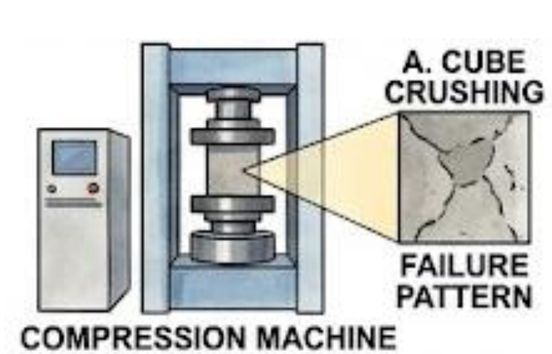
Evolution of the gypsum market between 2020 and 2030.

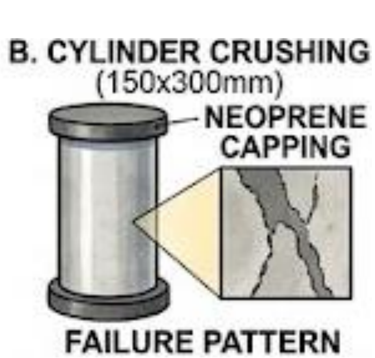
Qin et al. "Resource utilization and development of phosphogypsum-based materials in civil engineering."J. of Cleaner Prod. (2023)

Performance of PG in cement composites

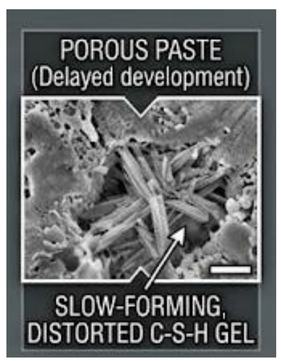
PG Dosage	Fresh Properties	Strength	Durability	Recommendation
<5%	Minimal effect	Neutral	Neutral	Safe replacement of gypsum
5–15%	Slight retardation	Improved or maintained	Improved	Optimum range for OPC
15–30%	Noticeable retardation	Good with activators	Improved	Preferred for blended cements Requires optimization
30–45%	Significant retardation	Acceptable with slag/MK	Good	
>45%	Severe retardation	Strength loss likely	Durability concerns	Not recommended without activation
Mechanism/ Challenges	• Sulfate-rich PG slows setting time • Requires admixtures	• Retarded hydration • DEF • Secondary C-S-H formation • Refined pore structure	• Expansion from ettringite • Gypsum dissolution • Pore refinement • Dense matrix	n/a







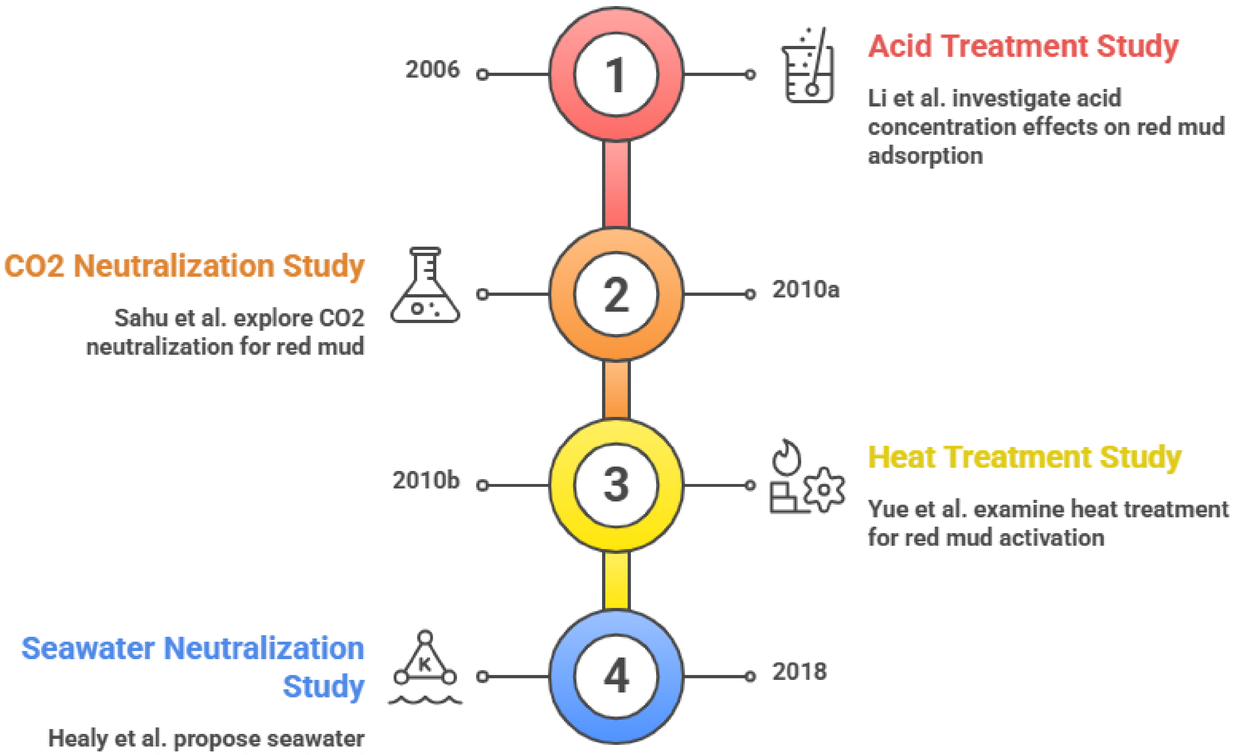




Xu et al. "Performance Control and Synergistic Modification Mechanism of Phosphogypsum-Based Cementitious Materials: A review.“ Buildings (2025)

Treatment of RM

Red Mud Neutralization Methods Over Time



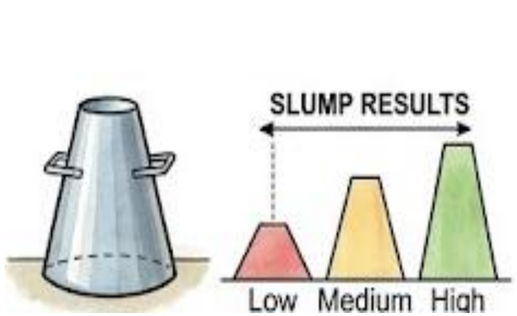
Comparison of Red Mud Neutralization Methods

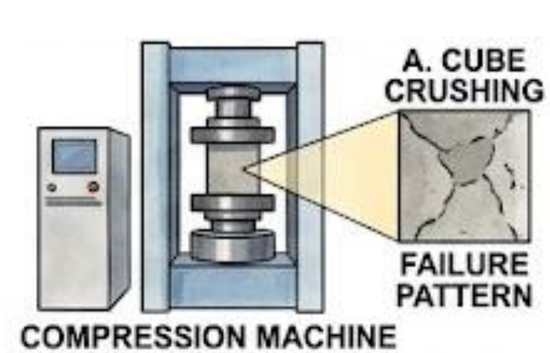
Characteristic	Acid Treatment	Heat Treatment	Seawater Neutralization	CO2 Neutralization
Process	Mixing with HCl or HNO3	Calcination at 600–1000 °C	Ion exchange with seawater	Passing CO2 into red mud solution
Key Factors	Acid concentration, mixing ratio, time, temperature	Temperature, time	Proximity to sea, transportation costs	CO2 concentration, stirring
Advantages	Increases specific surface area	Improves adsorption performance	Reduces alkali discharge	Reduces alkali discharge
Disadvantages	Produces acid waste, high cost	High energy consumption, negative economic benefit	Limited to coastal areas, transportation costs	Requires CO2 supply
Suitability	Effective for increasing surface area	Not recommended for red mud activation	Well-suited for coastal red mud yards	Effective for reducing pH

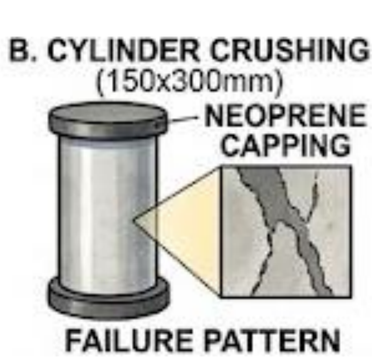
Wang & Liu "Applications of red mud as an environmental remediation material: A review."J. of Hazardous Mat. (2021)

Performance of RM in cement composites

RM Replacement	Fresh Properties	Strength	Durability	Recommendation
<5%	Minimal impact	Neutral	Neutral	Safe use
5–10%	Slight workability loss	Strength increase	Improved	Excellent
10–15%	Moderate slump loss	Peak performance	Improved	Optimum range
15–25%	Significant slump reduction	Slightly reduced	Good	Use admixtures
25–40%	Poor workability	Strength reduction likely	Variable	Requires activation
>40%	Severe workability issues	Strength retrogression	Good after treatment	Not suitable for OPC alone. Requires geopolymer/alkali activation
Mechanism/ Challenges	• High surface area • Angular particles • Requires admixtures	• Filler effect • Pozzolanic effect	• Improved ITZ • Pore refinement • Dense matrix	n/a











Mohammed et al. "A review on the utilization of red mud in concrete: Effects on fresh, mechanical, and durability properties.“ J. of Build. Eng. (2026)

Summary

Parameter	Phosphogypsum	Red Mud
Main Challenge	High SO_3, P_2O_5, radioactivity	High alkalinity, alkali content, radioactivity
Optimum OPC Replacement	10–30%	5–15%
Pretreatment Requirement	Moderate (Calcination / Seawater / Lime)	Moderate to High (Calcination / Seawater)
Workability	Moderate reduction	Significant reduction (fineness + morphology)
Strength Potential	High after activation	High after activation
Chloride Resistance	Low-Moderate	Excellent
Sulfate Resistance	Excellent	Variable
Carbon Reduction Potential	High (20-60% less GWP)	High (40-80% less GWP)
Geopolymer Suitability	Moderate	Excellent

For further information please contact authors:
fci@kaust.edu.sa

All Rights Reserved 2026