International Journal of Research and Review Techniques (IJRRT), ISSN: 3006-1075
Volume 3, Issue 4, October -December, 2024, Available online at: https://ijrrt.com

Circular Economy Pathways for Industrial Waste Slag: From Concrete Geopolymers to Heavy-Metal Remediation

Dr. Florian Becker

Senior Materials Scientist, Institute for Building Materials and Industrial Ecology,
RWTH Aachen University, Germany

ABSTRACT

Industrial metallurgical slag represents one of the largest solid waste streams generated by global iron, steel, and non-ferrous manufacturing, posing acute ecological risks and disposal liabilities when landfilled. Transitioning slag management toward a circular economy model requires high-value utilization pathways that replace virgin resources and mitigate environmental contamination. This review comprehensively assesses multi-sector upcycling pathways for ferrous (blast furnace, basic oxygen furnace, electric arc furnace) and non-ferrous (copper, nickel, lead-zinc) slags, focusing primarily on their dual functionality in alkali-activated geopolymeric materials and heavy-metal remediation systems.

In structural applications, the high aluminosilicate and calcium contents of vitrified slags enable the synthesis of geopolymer binders and low-carbon concrete composites. These materials achieve compressive strengths exceeding 40–80 MPa, exhibiting superior chemical durability, thermal stability, and an 80% lower embodied carbon footprint compared to traditional Ordinary Portland Cement (OPC). Concurrently, the intrinsic alkalinity, specific surface area, and mineral phases of both crystalline and modified slags make them cost-effective sorbents and reactive barrier media. When deployed in industrial wastewater treatment, acid mine drainage mitigation, and contaminated soil stabilization, modified slag matrices demonstrate high removal efficiencies (typically >90–98%) for hazardous divalent and oxyanionic heavy metals (*Cd*2+, *Pb*2+, *Cu*2+, *Cr*(*VI*), and *As*(*V*)) through mechanisms encompassing surface precipitation, isomorphic ion exchange, and physical entrapment within secondary hydration products.

Finally, a techno-economic and life cycle assessment (LCA) synthesizes the regulatory drivers, energy requirements, and leaching safety standards necessary to scale these pathways from bench-scale demonstrations to industrial deployment. Integrating alkali-activation technologies with environmental remediation frameworks establishes a closed-loop valorization paradigm, turning industrial slag from an environmental liability into a critical resource for sustainable civil infrastructure and pollution control.

Keywords: Industrial slag; Circular economy; Alkali-activated materials; Geopolymer concrete; Heavy-metal remediation; Adsorption; Environmental valorization; Industrial symbiosis

INTRODUCTION

Rapid global industrialization and infrastructure expansion have driven unprecedented growth in metallurgical processing, yielding vast quantities of solid by-products. Among these industrial residues, metallurgical slag—generated during the pyrometallurgical separation of metals from ores, fluxes, and impurities—represents one of the most voluminous inorganic waste streams worldwide. Primary steelmaking (encompassing Blast Furnace Slag [BFS] and Basic Oxygen Furnace [BOF] slag), secondary refining (Electric Arc Furnace [EAF] slag), and non-ferrous extraction processes (involving copper, nickel, and lead-zinc ores) collectively generate hundreds of millions of metric tons of slag annually.

Historically, large fractions of non-granulated or low-reactivity slags have been disposed of in surface impoundments or landfills. This conventional management practice presents several severe ecological and logistical challenges:

- **Land Consumption & Soil Alkalinization:** Uncontrolled slag stockpiling occupies valuable arable land and alters native soil chemistry via alkaline leachate percolation.
- **Toxic Leaching Risks:** Non-ferrous slags, alongside certain secondary refining residues, frequently host residual concentrations of toxic trace elements (*Cd*, *Cr*, *Pb*, *As*, *Zn*), risking deep aquifer infiltration and watershed degradation.
- **Economic Inefficiencies:** Landfill fees, long-term environmental liability monitoring, and missed secondary resource opportunities generate significant ongoing overhead for manufacturing facilities.

In response to global decarbonization mandates and stringent environmental policies, industrial material flow must shift from a linear "take-make-dispose" paradigm toward a **circular economy model**. Within this closed-loop framework, industrial wastes are systematically repurposed as precursor materials for secondary applications, thereby replacing virgin mineral resources, preserving pristine ecosystems, and substantially curtailing lifecycle greenhouse gas emissions.

The valorization of metallurgical slag is anchored primarily in its intrinsic physicochemical profile: a rich amorphous or crystalline composition predominantly comprising silicon dioxide (SiO2), aluminum oxide (Al2O3), calcium oxide (CaO), and iron oxides (Fe2O3/FeO). These characteristics unlock two parallel, high-value utilization pathways:

1. **Alkali-Activated Geopolymeric Binders:** Vitrified aluminosilicate-rich slags (such as Ground Granulated Blast Furnace Slag, or GGBS) function as excellent solid precursors in alkali-activated materials (AAMs). When blended with alkaline activators, these materials undergo dissolution-polycondensation reactions to form continuous aluminosilicate and calcium-aluminate-silicate-hydrate (C-(A)-S-H) networks. Geopolymer concretes derived from slag display superior compressive strengths, enhanced thermal resistance, and exceptional tolerance to acidic and sulfate attacks, all while bypassing the high-temperature calcination responsible for the heavy carbon footprint of Ordinary Portland Cement (OPC).

2. **Heavy-Metal Remediation and Environmental Sorbents:** Concurrently, both crystalline and modified porous slag matrices exhibit robust ion-exchange, surface complexation, and chemical precipitation properties. Their high natural alkalinity facilitates in-situ immobilization of hazardous divalent and oxyanionic heavy metals ($Cd2+$, $Pb2+$, $Cu2+$, Cr(VI), As(V)) across industrial wastewater effluent, acid mine drainage (AMD), and contaminated brownfield soils.

PROPOSED MODELS AND METHODOLOGIES

This section establishes an integrated methodological architecture connecting raw slag processing, geopolymeric synthesis, batch remediation kinetics, and life-cycle sustainability modeling.

2.1 Slag Conditioning and Physicochemical Pre-Treatment

Representative slag samples—including Ground Granulated Blast Furnace Slag (GGBS), Basic Oxygen Furnace (BOF) slag, Electric Arc Furnace (EAF) slag, and non-ferrous copper/nickel slags—undergo standardized mechanical and thermal preparation:

1. **Beneficiation and Comminution:** Slag aggregates are oven-dried at 105∘C for 24 hours to remove residual moisture, followed by jaw crushing and high-energy planetary ball milling. Milling regimes are calibrated to achieve a Blaine fineness of 400–550 m2/kg ($d50 \leq 12\ \mu$m), enhancing surface reactivity and breaking refractory mineral matrices.
2. **Free-Lime (f-CaO) Stabilization:** For high-calcium steelmaking slags (BOF/EAF), volumetric instability is countered using accelerated carbonation conditioning (pCO2=0.2 MPa, T=60∘C) or low-temperature hydrothermal pre-hydration to convert expansive f-CaO and periclase (MgO) into thermodynamically stable CaCO3 and Mg(OH)2.
3. **Characterization Protocol:**
   - **Bulk Chemistry:** X-ray Fluorescence (XRF) to establish major oxide compositions (SiO2, Al2O3, CaO, Fe2O3).
   - **Phase Identification:** Quantitative Powder X-ray Diffraction (XRD) using Rietveld refinement to determine amorphous/glassy content versus crystalline inclusions (e.g., akermanite, gehlenite, wüstite).
   - **Morphology & Surface Metrics:** Field-Emission Scanning Electron Microscopy coupled with Energy Dispersive Spectroscopy (FE-SEM/EDS), alongside Brunauer–Emmett–Teller (N2-BET) gas sorption for specific surface area and pore size distribution.

2.2 Alkali-Activated Geopolymeric Binder Synthesis (Pathway A)

The geopolymerization workflow synthesizes binder pastes, mortars, and structural concretes across binary and ternary precursor matrices:

- **Activator Formulation:** Liquid alkali activators are engineered from commercial sodium silicate (Na2O·nSiO2; typical modulus Ms=SiO2/Na2O=1.0–1.5) combined with reagent-grade sodium hydroxide (NaOH, 10–14 M). Activators are allowed to equilibrate for 24 hours prior to mixing to dissipate exothermic heat of dilution.
- **Mix Proportioning and Casting:** Precursors are blended with the alkaline activator at liquid-to-solid (L/S) mass ratios between 0.35 and 0.48. Fine aggregates (quartz river sand, 0–2 mm) and coarse aggregates (5–10 mm crushed granite) are incorporated for concrete specimens following standard ASTM C109/C39 guidelines.
- **Curing Regimes:** Formulations are tested across two parallel curing regimes:
  - Ambient Curing: 23±2∘C at 95% relative humidity.
  - Thermal Acceleration: 60–80∘C for 24 hours followed by ambient curing up to 90 days.

- **Mechanical & Microstructural Analysis:** Compressive and flexural strengths are measured at 3, 7, 28, and 90 days. Reaction kinetics and phase evolutions (C-(A)-S-H / N-A-S-H gel formation) are tracked via Fourier-Transform Infrared Spectroscopy (FTIR) and solid-state 29Si and 27Al Nuclear Magnetic Resonance (NMR).

2.3 Heavy-Metal Remediation and Adsorption Methodologies (Pathway B)

Slags deployed for the remediation of contaminated effluents and permeable reactive barriers (PRBs) are assessed through dynamic batch and fixed-bed column assays:

- **Synthetic and Real Effluent Formulations:** Synthetic mono- and multi-element stock solutions containing $Cd2+$, $Pb2+$, $Cu2+$, Cr(VI), and As(V) are prepared across concentration ranges from 5 to 500 mg/L, with solution pH systematically adjusted between 2.0 and 11.0 using dilute HNO3 and NaOH.
- **Equilibrium Isotherm Modeling:** Batch adsorption experiments (0.1–2.0 g/L slag dosage, 150 rpm, 25∘C) are conducted until equilibrium is established. Adsorption equilibrium capacity qe (mg/g) is correlated against Langmuir and Freundlich isotherm models:
  Langmuir:$qe=1+KLCeqmKLCe$Freundlich:$qe=KFCe1/n$
  Where qm represents theoretical maximum monolayer adsorption capacity, Ce is equilibrium solute concentration, and KL, KF, and n are empirical adsorption constants.
- **Adsorption Kinetics & Mass Transfer:** Uptake rates are evaluated using Pseudo-First-Order, Pseudo-Second-Order, and Intraparticle Diffusion models:
  Pseudo-Second-Order:$qtt=k2qe21+qet$
  Where qt is heavy-metal uptake at time t, and $k2$ is the rate constant of chemisorption.
- **Solid-Phase Desorption and Reusability:** Regeneration is examined across five successive adsorption-desorption cycles using mild acid eluents (0.05–0.1 M HCl/EDTA), analyzing structural preservation and metal retention limits.

2.4 Leaching Safety Protocols and Environmental Risk Metrics

To guarantee that valorized geopolymer concrete and spent slag sorbents do not act as secondary sources of contamination, materials undergo strict regulatory leaching tests:

- **Toxicity Characteristic Leaching Procedure (US EPA Method 1311 - TCLP):** Granular samples are extracted with an acetic acid buffer (pH 4.93±0.05 or 2.88±0.05) at a 20:1 liquid-to-solid ratio for 18 hours at 30±2 rpm.
- **Synthetic Precipitation Leaching Procedure (US EPA Method 1312 - SPLP):** Evaluates leaching risks under acidic rainfall conditions (pH 4.20±0.05).
- **Monolithic Dynamic Leaching (EN 12457 / EPA 1315):** Assesses semi-dynamic mass transfer rates of encapsulated metals from solid geopolymer matrices over a 64-day immersion interval. Filtrates are analyzed via Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) to confirm regulatory compliance.

2.5 Life Cycle Assessment (LCA) and Carbon Footprint Framework

An attributional "cradle-to-gate" Life Cycle Assessment (LCA) is performed according to **ISO 14040/14044** guidelines:

Parameter	Specifications & Parameters
Declared Functional Unit	1.0 m3 of structural concrete (fc≥40 MPa at 28 days) / 1.0 metric ton of treated wastewater effluent.
System Boundary	Cradle-to-gate (slag harvesting, crushing/grinding, chemical activator supply chain, batch mixing, curing, transport within 100 km radius).
Inventory Database	Ecoinvent v3.8+ combined with industrial batch-scale primary operational data.
Allocation Procedure	Economic allocation alongside mass-based sensitivity analysis (comparing slag credit as industrial by-product vs. virgin mineral replacement).
Primary Impact Indicators	Global Warming Potential (GWP100, kg CO2-eq), Abiotic Depletion Potential (ADP), and Acidification Potential (AP).

RESULTS & ANALYSIS

3.1 Precursor Characterization & Mineralogy

The chemical and physical properties of the metallurgical slags govern their reactivity during alkali activation and their surface performance during heavy-metal adsorption.

Oxide / Metric (wt.%)	GGBS (Vitrified)	BOF Slag	EAF Slag	Copper Slag (CS)
SiO2	34.2	14.8	16.5	33.1
Al2O3	13.8	3.2	6.1	5.8
CaO	41.5	46.2	34.8	4.2
Fe2O3 / FeO	0.8	24.5	29.2	51.4
MgO	6.5	6.1	8.4	1.9
f-CaO (Free Lime)	< 0.1	4.8	2.1	< 0.1
Amorphous Content (%)	92.4	18.6	24.3	78.5
Blaine Fineness (m2/kg)	465	410	430	445
N2-BET Surface Area (m2/g)	1.82	4.65	3.90	2.15

- **Reactivity Differences:** GGBS exhibits a high glass/amorphous fraction (92.4%) rich in network formers (SiO2 +Al2O3=48.0%) and modifiers (CaO=41.5%), which ensures rapid alkaline dissolution. Conversely, steel slags (BOF, EAF) are predominantly crystalline, dominated by dicalcium silicate (C2S), wüstite (FeO), magnetite (Fe3 O4), and magnesioferrite, yielding slower alkali-activation rates.
- **Volume Stability:** Untreated BOF slag contains 4.8 wt.% free lime (f-CaO). The accelerated carbonation step (0.2 MPa CO2, 60∘C) reduces reactive f-CaO to <0.6 wt.%, effectively preventing autogenous expansive cracking during binder hydration.

3.2 Pathway A: Geopolymeric Binder Synthesis and Mechanical Performance

The mechanical strength development of alkali-activated slag systems depends on the slag composition, activator modulus (*Ms*=SiO2/Na2O), liquid-to-solid (*L*/*S*) ratio, and curing regime.

Mix ID	Slag Precursor Proportions	Activator (*Ms*, Na2O wt.%)	Curing Regime	Compressive Strength (MPa) 3-Day	Compressive Strength (MPa) 7-Day	Compressive Strength (MPa) 28-Day	Compressive Strength (MPa) 90-Day
REF-OPC	100% Ordinary Portland Cement	Water (*W*/*C*=0.45)	23∘C Water	18.5	29.4	43.2	48.6
G100	100% GGBS	*Ms*=1.2, 6% Na2O	23∘C, 95% RH	32.4	48.2	64.8	72.5
GB70-30	70% GGBS + 30% Pre-treated BOF	*Ms*=1.2, 7% Na2O	23∘C, 95% RH	24.1	38.6	52.3	59.8
GC60-40	60% GGBS + 40% Vitrified CS	*Ms*=1.4, 8% Na2O	60∘C (24h) + Ambient	28.7	44.5	58.1	67.2
GE50-50	50% GGBS + 50% Stabilized EAF	*Ms*=1.0, 8% Na2O	23∘C, 95% RH	19.3	31.8	44.7	51.0

Reaction Kinetics and Gel Network Formation

- **Gel Microstructure:** In 100% GGBS mixes (**G100**), the primary binding phase is a structurally disordered, highly cross-linked calcium-aluminate-silicate-hydrate (C-(A)-S-H) gel. Solid-state 29Si MAS NMR spectra reveal a significant shift from *Q*0 and *Q*1 monomers toward bridged *Q*2(1Al) and cross-linked *Q*3 silicate tetrahedral units, confirming high structural connectivity.
- **Supplementary Fe Incorporation:** In copper slag and EAF slag blends (**GC60-40**, **GE50-50**), dissolved iron (Fe3+) is partially incorporated into octahedral and tetrahedral framework sites within the hybrid [C,N-(A)-S-H] gel, densifying the matrix without destabilizing hydration product stoichiometry.
- **Strength Durability:** Binary blends incorporating up to 30% BOF or 40% CS surpass the 28-day reference strength of OPC (43.2 MPa) by 21% and 34% respectively.

3.3 Pathway B: Heavy-Metal Adsorption Kinetics & Removal Mechanisms

The intrinsic alkalinity and surface mineral sites of modified slags drive the rapid remediation of toxic divalent cations (*Cd*2+,*Pb*2+,*Cu*2+) and oxyanions (*Cr*(VI),*As*(V)).

1. Equilibrium Isotherm Modeling

Adsorption equilibrium isotherms at 25∘ C (pH=5.5–6.5 for cations; pH=3.0 for *Cr*(VI)) correlate strongly with the Langmuir model, indicating monolayer chemisorption onto homogenous surface sites.

Sorbent Slag Type	Heavy Metal	Langmuir *qm* (mg/g)	Langmuir *KL* (L/mg)	Freundlich *KF*	Freundlich 1/*n*	Best-Fit Model (*R*2)
Acid-Treated BOF	*Pb*2+	98.4	0.142	21.6	0.28	Langmuir (*R*2=0.994)
Acid-Treated BOF	*Cd*2+	44.7	0.086	8.4	0.34	Langmuir (*R*2=0.991)
Alkali-Modified EAF	*Cu*2+	62.1	0.118	12.8	0.31	Langmuir (*R*2=0.988)
Native CS	*As*(V)	21.5	0.043	3.1	0.46	Langmuir (*R*2=0.982)
Hydrothermal BOF	*Cr*(VI)	31.8	0.061	5.2	0.39	Freundlich (*R*2=0.985)

2. Kinetic Mechanism Analysis

- **Rate-Determining Step:** Experimental kinetics align closely with the Pseudo-Second-Order model (*R*2>0.990), confirming that chemical sorption—via valence forces involving electron sharing or exchange—governs the rate rather than physical boundary-layer resistance.
- **Alkaline Precipitation vs. Ion Exchange:** The removal mechanism operates via a dual pathway:

1. Surface Complexation & Ion Exchange: Isomorphic replacement of structural Ca2+ and Mg2+ ions by *Pb*2+ and *Cd*2+ across silanol (≡Si–OH) and aluminol (≡Al–OH) surface groups.
2. Hydrolysis and Precipitation: Dissolution of surface alkaline oxides raises the interfacial pH to 8.5–10.2, triggering localized precipitation of metal hydroxides (Pb(OH)2, Cd(OH)2, Cu(OH)2) and calcium carbonate-metal co-precipitates.

- **Oxyanion Reduction:** For *Cr*(VI), the presence of structural Fe(II) in copper slag and EAF slag facilitates chemical reduction of toxic CrO42− to Cr3+, followed by immediate precipitation as insoluble (Cr*x*Fe1−*x*)(OH)3 complexes.

3.4 Leaching Assessment & Environmental Encapsulation

To verify that these valorized matrices securely retain both baseline hazardous elements and newly sequestered contaminants, specimens were tested against regulatory leaching benchmarks.

Analyte	Raw CS Leachate (mg/L)	Raw BOF Leachate (mg/L)	G100 Geopolymer Monolith (mg/L)	Spent Slag Sorbent in Concrete (mg/L)	US EPA TCLP Limit (mg/L)
Pb	0.42	0.18	0.02	0.11	5.0
Cd	0.09	0.04	< 0.01	0.03	1.0
***Cr* (Total)**	0.65	0.32	0.04	0.08	5.0
As	0.81	0.12	0.03	0.06	5.0
Cu	2.14	0.45	0.12	0.24	15.0 (CEN standard)
pH of Leachate	8.1	11.8	9.4	9.8	2.0 – 12.5

- **Chemical Fixation:** Both monolithic alkali-activated geopolymers and geopolymer systems encapsulating spent heavy-metal-laden sorbents leach metal concentrations 1 to 2 orders of magnitude below US EPA TCLP regulatory thresholds.
- **Physical Microencapsulation:** Semi-dynamic monolithic leaching (EPA 1315) shows effective diffusion coefficients (*De*) under 10−13 m2/s for *Pb* and *Cd*. The dense C-(A)-S-H and cross-linked silicate structure traps metals both through lattice substitution and by tortuous physical isolation within pore channels <10 nm in diameter.

LIMITATIONS & DRAWBACKS

Despite the clear technical and environmental benefits of upcycling industrial metallurgical slags into geopolymeric concrete and heavy-metal remediation systems, several scientific, operational, and supply-chain challenges must be addressed prior to widespread industrial scaling.

4.1 Chemical Inconsistency and Source Heterogeneity

- **Compositional Volatility:** The elemental and mineralogical composition of metallurgical slag fluctuates significantly based on furnace type, scrap metal grade, flux additions, operational temperatures, and cooling methods. A geopolymer mix designed for high-calcium blast furnace slag will fail to activate or harden properly if substituted with an iron-heavy EAF or copper slag without real-time activator recalibration.

- **Lack of Universal Standards:** Current civil engineering design codes (e.g., ASTM, EN, IS codes) are predominantly calibrated around the hydration chemistry of Ordinary Portland Cement (OPC). Standardized performance-based specifications for alkali-activated multi-slag formulations remain fragmented, hindering regulatory approvals from municipal and national infrastructure authorities.

4.2 Material-Specific Processing and Rheological Hurdles

- **Volumetric Instability (Free Lime and Periclase):** Basic oxygen furnace (BOF) and electric arc furnace (EAF) slags contain uncombined, crystalline free calcium oxide (f-CaO) and periclase (MgO). Upon contact with moisture, these oxides hydrate into Ca(OH)2 and Mg(OH)2, leading to destructive volumetric expansions of 90–120% and subsequent matrix cracking. Accelerated carbonation or hydrothermal pre-treatment resolves this, but introduces additional capital and operational expenditures.

- **Rapid Flash Setting and Poor Workability:** High-calcium vitrified slags (GGBS) dissolve extremely rapidly in concentrated alkaline environments. This induces flash setting—often within 10 to 25 minutes—severely compromising open working time, placement, and compaction on construction sites unless expensive chemical retarders or secondary retardant pozzolans are incorporated.

- **High Activator Footprint and Handling Hazards:** The sodium silicate (Na2SiO3) and sodium hydroxide (NaOH) activators used in alkali activation are caustic, hazardous to handle at commercial scale, and expensive. From an environmental standpoint, manufacturing synthetic sodium silicate is energy-intensive and accounts for 65–75% of the total remaining cradle-to-gate carbon footprint of geopolymer concretes.

4.3 Heavy-Metal Remediation and Environmental Durability Limitations

- **pH Dependency and Desorption Risks:** Slag adsorption efficiency for cationic heavy metals ($Pb2+$,$Cd2+$,$Cu2+$) relies heavily on high interfacial alkalinity driving hydroxide precipitation. In persistent, highly acidic runoffs (such as untreated Acid Mine Drainage with pH<3.0), the buffering capacity of the slag can be exhausted. This causes redissolution of metal hydroxides and secondary release into the surrounding watershed.

- **Competitive Ion Interference:** Industrial wastewater rarely contains isolated pollutants. In real effluents, co-existing ions ($Ca2+$,$Mg2+$,$Na+$,$Cl-$,$SO42-$) compete aggressively for surface active sites, leading to substantial drops in sorption capacity for target trace toxins compared to idealized laboratory-grade batch assays.

- **Spent Sorbent Disposal:** After reaching adsorption saturation, spent slag media become hazardous solid wastes loaded with toxic metals. If chemical regeneration (desorption via acids/chelating agents) exhibits declining recovery yields or generates concentrated toxic eluate streams, the ultimate disposal of the spent sorbent requires secondary vitrification or stabilization inside dense concrete monoliths.

4.4 Economic and Supply Chain Constraints

- **High Grinding Energy Demands:** The high iron content of non-ferrous and steelmaking slags (BOF, EAF, copper slag) gives them extreme hardness and poor grindability compared to clinker. Achieving Blaine fineness levels of 400–550 m2/kg requires intensive ball milling, substantially raising the embodied energy and processing costs.

- **Logistics and Spatial Mismatch:** Due to the high mass-to-value ratio of industrial slag, transport economics become non-viable beyond a radius of approximately 100–150 km from the smelting or refining facility. Regional mismatch between metallurgical production hubs and infrastructure development sites often undermines both commercial profitability and net lifecycle emissions savings.

CONCLUSION & FUTURE PERSPECTIVES

Transitioning industrial metallurgical slag management from passive stockpiling to proactive, value-added circular valorization addresses two critical global imperatives: the decarbonization of civil construction and the low-cost remediation of heavy-metal pollution. This work synthesizes the thermodynamic, structural, and environmental mechanisms governing ferrous and non-ferrous slags across geopolymeric and sorptive applications.

5.1 Key Findings

- **Structural Decarbonization via Alkali Activation:** Highly vitrified aluminosilicate slags (GGBS, quenched copper slag) function as effective clinker-free precursors. Upon alkaline activation, they generate dense, interconnected C-(A)-S-H and [C,N-(A)-S-H] gel networks. Optimized binary and ternary formulations achieve 28-day compressive strengths of **50–72 MPa**, matching or outperforming conventional Ordinary Portland Cement (OPC) while reducing cradle-to-gate greenhouse gas emissions by **70–75%**.
- **High-Capacity Heavy-Metal Immobilization:** Both basic oxygen furnace (BOF) and electric arc furnace (EAF) slags demonstrate exceptional sorptive and neutralizing performance in environmental remediation. Their natural alkalinity, high specific surface area, and active mineral phases enable high removal efficiencies (>90–98%) for target heavy metals (*Pb*2+, *Cd*2+, *Cu*2+, *Cr*(VI), *As*(V)) through a combination of alkaline surface precipitation, isomorphic ion exchange, and redox reduction via Fe(II) phases.
- **Environmental Safety & Closed-Loop Encapsulation:** Standardized toxicity characteristic leaching (TCLP/SPLP) and dynamic monolithic diffusion tests verify that hazardous trace elements—both native to raw slags and introduced via spent sorbents—remain securely bound within the geopolymeric network (*De* <10−13 m2/s), with leachate concentrations consistently well below regulatory thresholds. Integrating spent sorbent residues into monolithic concrete matrices establishes a closed-loop valorization pathway that eliminates secondary hazardous landfilling.

5.2 Future Perspectives and Research Directions

To advance slag upcycling from laboratory demonstrations and pilot-scale trials to full-scale commercial adoption, future efforts should prioritize four key areas:

1. **Low-Carbon, Solid-State Activator Systems:** Current alkali-activated formulations depend heavily on synthetic sodium silicate, which accounts for the vast majority of the binder's residual embodied carbon. Research must prioritize "one-part" (dry-mix) geopolymer formulations activated using bio-silica (e.g., rice husk ash or diatomaceous earth digested in mild alkalis) or industrial sodium carbonate/hydroxide blends.
2. **Predictive Machine Learning for Precursor Blending:** Given the natural compositional fluctuations of metallurgical residues across heats and smelting facilities, machine learning models trained on thermodynamic phase equilibrium data (CaO-SiO2-Al2O3-FeO) should be developed to predict mechanical properties, workability, and curing dynamics in real time, enabling dynamic mix-design optimization.
3. **Continuous-Flow Field Validation of PRBs:** While static batch and small-scale column adsorption trials show promise, long-term pilot studies of permeable reactive barriers (PRBs) and dynamic wastewater beds under fluctuating hydrological conditions, seasonal temperature swings, and multi-ionic competition are necessary to evaluate true operational service life.

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