

Solid Waste Resource Utilization • Green Mine Technology Application

**Coupled Application of Physical-Field Mineral Processing
and Geopolymer Cementitious Material**

Summary of Integrated Solution for Zero-Waste Mining, Processing and Metallurgy

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Executive Summary

Executive Summary

Key Indicators	Quantitative Conclusion	Supporting Stage
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Source Ineffective Processing Volume Reduction	Reduced by 30%–50%	Physical-field intelligent pre-concentration
Subsequent Whole-Process Energy/Water/Steel Consumption	Reduced by approx. 40%	Pre-concentration waste discarding + dry sorting
Cementitious Material Dosage (vs. Cement)	Reduced to 60%–70%	Geopolymer cementitious material
Comprehensive Backfill Cost	Decreased by approx. 1/3	Cemented backfill replacing cement
Carbon Emissions	60%–80% lower than cement	Calcination-free preparation process
Heavy metal immobilization rate	Generally 90%–99%+	Three-dimensional aluminosilicate network

China generates over 11 billion tons of solid waste annually. Among this, metal mine tailings exceed 1.5 billion tons per year, with cumulative historical stockpiling over 20 billion tons; coal gangue annual output is approximately 700 million tons, with cumulative stockpiling over 5 billion tons; and fly ash emissions from the power industry are approximately 650 million tons per year. Behind these figures lies a long-unresolved structural contradiction: solid waste governance has long remained in the passive mode of end-of-pile stockpiling and post-event disposal, while the material properties of mining, processing and metallurgy three major stages are wasted at the very moment they are generated.

On December 19, 2025, the State Council Executive Meeting deployed a comprehensive solid waste treatment action, explicitly requiring construction of a comprehensive solid waste treatment system of source reduction, process control, end utilization and whole-chain harmlessness according to the principles of reduction, resource utilization and harmlessness. The key word in this statement is source — the focus of governance must move forward from after solid waste is

generated to while solid waste is being generated, or even before solid waste is generated.

This report proposes and analyzes a highly compatible technical path: using physical-field mineral processing technology to complete source separation and purification, and geopolymer cementitious material to complete end cementation and remanufacturing. The two are coupled to form a material closed loop, achieving zero-waste mining, processing and metallurgy.

The essential feature of physical-field mineral processing (gravity separation, magnetic separation, electrical separation, photoelectric/rays intelligent sorting, and external field enhancement means such as microwave, ultrasonic and electric field) is that it does not change the inherent physical and chemical properties of minerals during separation, and requires no chemical reagents. It puts the industry principle of discard early when possible, more crushing less grinding into practice: separating gangue and low-grade waste rock at the coarse particle stage, reducing subsequent ineffective processing volume from the source. Public engineering data shows that AI photoelectric intelligent pre-concentration can precisely discard waste rock at 10–80 mm coarse particle size, reducing source ineffective processing volume by 30%–50%; after more than 30 low-grade iron mines adopted photoelectric pre-concentration, the average waste discarding rate exceeded 50%, and subsequent whole-process energy, water and steel consumption decreased by approximately 40%; dry magnetic separation pre-concentration can save over 90% of water. The separated waste rock, gangue and concentrate are themselves three types of materials that can be directionally utilized separately.

The essential feature of geopolymer cementitious material is no high-temperature calcination, using solid waste as raw material, and capable of forming a three-dimensional aluminosilicate network at room or low temperature. Compared with

traditional Portland cement, its production process can reduce CO₂ emissions by approximately 80%; fly ash-based geopolymer 28-day compressive strength can reach 55.6–136 MPa; it does not decompose at 1000–1200 °C, and its decomposition rate in 5% sulfuric acid solution is only 1/12 of Portland cement; its immobilization efficiency for heavy metals such as lead, zinc, chromium and cadmium generally exceeds 90%, with some systems reaching over 99%. This means it can not only consume the fine tailings, smelting slag and dust produced by physical-field separation, but also permanently lock the heavy metals within the cementitious network.

The internal logic of coupling the two is clear and tight: physical-field technology is responsible for disassembling mixed materials into four material streams: valuable concentrate, construction-materializable aggregate, active aluminosilicate fine material, and heavy metal enriched phase, while geopolymer material provides large-scale, high-value and stable outlets for the latter three types, and locks heavy metals in a three-dimensional network of quasi-geological minerals. The interface between them is the material flow itself, requiring no additional adaptation.

Economic viability has been engineering-verified. A subsidiary of Tongling Nonferrous uses blast furnace slag, steel slag and industrial by-product gypsum to prepare new low-carbon cementitious material. Under equivalent conditions, its dosage is approximately 60%–70% of Portland cement, reducing mine backfilling cost by about one-third. Over three years, cumulative sales reached 1.13 million tons, collaboratively disposing of 10 million tons of mine tailings, reducing carbon emissions by nearly 1.3917 million tons, and was selected as a typical case of pollution reduction and carbon reduction synergy for zero-waste cities by the Basel Convention Asia-Pacific Regional Center. After Shishudi Gold Mine adopted low-carbon solid waste cementitious material to replace cement, it saved over 50% of

cementitious material, increased tailings utilization by over 10%, reduced backfilling cost by over 30%, and reduced carbon emissions by 90%.

The policy environment is already mature. The Resource Tax Law of the People's Republic of China provides reductions or exemptions for mining associated ores, low-grade ores and tailings, with tailings reduction ratio up to 50% or even full exemption; coal resource tax from backfill mining replacement is reduced by 50%; solid waste comprehensively utilized and meeting environmental standards is temporarily exempt from environmental protection tax; related product revenue is included at 90% when calculating taxable income. Green mine construction has been incorporated into local government performance evaluation systems. This path is no longer just environmental responsibility, but a growth curve that can be financially justified.

The conclusion of this report is: physical-field mineral processing technology and geopolymer cementitious material are not two independent technologies, but the two ends of a material closed-loop system. The former solves separable, cleanable and economical, while the latter solves usable, stable and durable. The coupling of the two can restore solid waste from mining, processing and metallurgy three major stages from environmental burden to secondary mineral resources, providing a technically feasible, economically reasonable, policy-adaptable and replicable implementation path for zero-waste mining, processing and metallurgy.

I. Introduction: Mining-Metallurgy Solid Waste Governance Must Shift from "End-of-Pipe" to "Source"

Mining, processing and metallurgy are basic industries of the national economy, and also the industrial category with the largest solid waste generation. To understand why this technical path works, one must first return to the long-

standing structural contradictions in the industry and the fundamental adjustments that have taken place in policy direction.

(I) A Contradiction Repeatedly Confirmed but Long Unresolved

A basic characteristic of China's mineral resources is that there are many co-associated components, many low-grade ores, and fine dissemination grain size. This characteristic determines the inherent defects of the traditional mining-processing-metallurgy flow: in order to recover one or two main metals, all ore must be ground fine, all material must go through a long flow, and associated components and gangue are all processed together in this process, ultimately discharged in the form of tailings, waste rock and smelting slag.

Data confirms this judgment. By the end of the 15th Five-Year Plan, cumulative stockpiling of bulk solid waste in China is enormous, with metal mine tailings historical stockpiling total over 20 billion tons, and coal gangue cumulative stockpiling over 5 billion tons. These materials are not only land occupation and safety risks — tailings dam failure risk has long ranked first among major mine risks — but also wasted secondary resources.

The practice of Panxi Hongge Vanadium-Titanium Magnetite Mine is highly convincing: after technical transformation for tailings re-recovery, TiO_2 grade in tailings dropped below 4%, and annually newly added titanium concentrate 50,000 tons and iron concentrate 21,700 tons were recovered from tailings, equivalent to turning a tailings pond that has been stockpiled for many years into an above-ground mine with continuous output.

The problem is not that tailings contain no resources, but that the material flow direction of the traditional flowsheet is one-way: ore → concentrate → tailings → tailings pond. Once entering the tailings pond, the resource attribute is downgraded to an environmental attribute, and recovering it requires paying secondary mining costs and environmental costs.

(II) Policy Has Clearly Shifted Governance Focus Forward to the Source

On December 19, 2025, the State Council Executive Meeting deployed a comprehensive solid waste treatment action, proposing to firmly curb the growth momentum of solid waste, and according to the principles of reduction, resource utilization and harmlessness, to construct a comprehensive solid waste treatment system of source reduction, process control, end utilization and whole-chain harmlessness. Source reduction ranks first among the four items — this is not a rhetorical order, but a fundamental adjustment of governance logic.

Supporting policy tools have already formed synergy:

- **Quantitative targets: bulk solid waste comprehensive utilization rate reaches 57% in 2025, and resource utilization rate exceeds 60% in 2030;**
- **Tax incentives: Resource Tax Law provides reductions/exemptions for associated ores, low-grade ores and tailings; coal resource tax from backfill mining replacement is reduced by 50%; comprehensively utilized solid waste is temporarily exempt from environmental protection tax; related product revenue is included at 90% for taxable income;**
- **Assessment constraints: green mine construction is incorporated into government performance assessment and leading cadres' natural resource asset departure audit evaluation indicator system; many regions require 95% of licensed in-production large and medium mines to build province-level+ green mines by the end of the 15th Five-Year Plan;**
- **Value orientation: the Ministry of Ecology and Environment continues to promote zero-waste city construction, with 113 cities implementing over 3000 construction projects, and promotes extension of zero-waste group pilots to large industrial groups.**

The policy direction is very clear: whoever first converts solid waste into products at the source will first gain cost advantages and green premiums.

(III) Analytical Framework of This Report

This report does not discuss individual technologies in isolation, but analyzes physical-field mineral processing technology and geopolymer cementitious material as a coupled system. The whole report follows the following logical thread: technical principles → coupling mechanism → stage-by-stage application → comprehensive benefits → practical foundation → conclusions and recommendations.

Chapters 4 to 6 correspond to the three stages of mining, processing and metallurgy respectively, answering the same question one by one: in this stage, what material streams does physical-field technology cut out, and what does geopolymer material turn them into respectively.

II. Principles and Capability Boundaries of Two Key Technologies

The two ends of the coupling system are separation and cementation. To understand why the coupling works, we need to first clarify the capability boundaries of the two technologies respectively — what each can and cannot do determines where the coupling interface lies.

(I) Physical-Field Mineral Processing: Efficient Green Separation Without Changing Mineral Nature

Physical-field mineral processing is the entrance of the coupling system. Its capability upper limit is determined by physical property differences, while its

value upper limit is determined by the timing of separation — the earlier the separation, the more subsequent steps are saved.

1. Technical Principles and Categories

The sorting basis of physical mineral processing is the differences in physical properties between minerals such as density, magnetism, conductivity, and surface optical characteristics. Its essential feature is that the sorting process does not change the inherent physical and chemical properties of the minerals themselves in the slightest. This forms a fundamental difference from processes relying on chemical reagents such as flotation, which is also why it is called green separation.

Technology Category	Sorting Basis	Main Use	Applicable Particle Size
Gravity Separation	Mineral density (specific gravity) difference	Main method for tungsten-tin ore and coal	Several hundred mm to below 1 mm
Magnetic Separation	Mineral magnetism difference	Iron-manganese ore separation, non-ferrous/rare metal cleaning, non-metallic iron removal, heavy medium recovery	Dry for coarse particles, wet for fine particles
Electrical Separation	Mineral conductivity and other electrical property differences	Non-ferrous/ferrous/rare metal cleaning, diamond and graphite sorting	Pre-drying and desliming required
Intensive Sorting	Optical, X-ray, radioactive characteristics	Pre-concentration waste rock discarding (lump ore stage)	10–80 mm (XRT)
Friction Separation, Bounce Separation	Friction coefficient, collision restitution coefficient difference	Specific non-metallic mineral sorting	Depends on mineral type

On top of these categories, external field enhancement technology is pushing separation precision to new levels: microwave uses selective heating and micro-explosion effects to promote liberation of lattice inclusion impurities; ultrasonic waves strengthen interfacial reactions and impurity peeling through cavitation effects, with ultrasonic leaching metal amount increased by 20% under the same conditions compared with conventional methods; electric fields improve separation efficiency by changing particle surface charge distribution, promoting particle collisions and lattice destruction.

Synergy of multiple physical fields (such as magnetic separation-acid washing, microwave-acid leaching, ultrasonic-flotation, temperature-pressure-chemical) has become the mainstream direction for processing complex refractory materials.

2. Core Engineering Value: Structural Cost Reduction Brought by Discarding Early When Possible

The most direct value of physical-field mineral processing technology in the mining-processing-metallurgy field is to support implementation of the industry principle of more crushing less grinding, discard early when possible. Pre-concentration waste discarding is to discard part of low-grade waste rock before fine crushing, grinding-separation or cleaning operations, thereby reducing subsequent operation load. Its benefits have been verified on multiple mineral types:

- **Significant source reduction effect: AI photoelectric intelligent pre-concentration using X-ray transmission (XRT) or high-definition vision technology can precisely identify and discard waste rock at 10–80 mm coarse particle size, directly reducing ineffective processing volume by 30%–50%;**
- **Replicable scale benefits: After more than 30 low-grade iron mines adopted AI photoelectric pre-concentration, the average waste discarding**

rate exceeded 50%, and subsequent whole-process energy, water and steel consumption decreased by approximately 40%;

- **Outstanding water saving effect:** Magnetite adopting high-efficiency dry magnetic separation pre-concentration can save over 90% of water compared with traditional wet method, especially suitable for arid and water-deficient mining areas;
- **Specific mine indicators:** Dajishan Tungsten Ore Processing Plant uses manual positive/negative hand sorting for +80 mm ore and XRT pre-concentration for –80+16 mm. In 2021, the annual average waste rock sorting rate was 52.87%, and ore qualification rate was 92.77%. For hand sorting, the waste discarding rate can reach 40%–60%;
- **Improved recovery rate:** Application practice of large-dry magnetic separation technology in the four major Panxi mining areas shows that its effect in reducing mining dilution rate and improving ore recovery rate is very significant;
- **Enhanced recovery rate:** Panxi Hongge Vanadium-Titanium Magnetite Mine, through external magnetic separator pre-concentration process innovation, achieved total iron recovery rate 5.96 percentage points higher than the national demonstration base planning target.

3. Separation Capability on the Solid Waste Side

The capability of physical-field technology is not limited to run-of-mine pre-concentration; it also constitutes a key separation means on the solid waste side: magnetic separation can recover scrap steel from steel slag and iron-aluminum resources from red mud; electrical separation can recover valuable metals such as copper and aluminum from municipal solid waste; physical mineral processing processes for industrial waste have the advantages of low energy consumption and low pollution.

Taking the entrusting party Huzhu Green Building (Beijing) Technology Co., Ltd. as an example, its core physical method material separation technology adopts magnetic, gravity, acoustic, electrical, optical and other multi-physical-field impurity removal processes, and achieves precise separation and purification of valuable components in solid waste through independently developed physical-field mineral separation equipment, requiring no chemical reagents, being environmentally friendly, low energy consumption and high efficiency, and supporting independent intellectual property rights such as Ultra-Pure Quartz Permanent Magnet High-Intensity Magnetic Separation and Purification Machine Control Software.

Among them, the most representative is the 3T (Tesla) gathered-magnet permanent-magnet high-intensity magnetic technology. This technology originated from the national key project completed by Wang Yuxian et al. of the Chinese Academy of Geological Sciences from 1996 to 2000. The self-developed gathered-magnet permanent-magnet high-intensity magnetic separation equipment has a field strength of 2.8–3.0 T. The State Science and Technology Commission commissioned the Ministry of Geology and Mineral Resources to conduct achievement evaluation, and the evaluation committee concluded that the gathered-magnet permanent-magnet high-intensity magnetic separation technology has reached the international advanced level.

Its engineering data is highly persuasive:

Verification Direction	Conditions and Data	Data Source
Desulfurization	Shougang Power Plant Datong steam coal: raw coal sulfur 1.57%, pyritic sulfur 0.97% → clean coal sulfur 0.63%, total coal desulfurization rate 61%, inorganic sulfur	National Coal Inspection Center

	desulfurization rate 81%	
Quality Improvement (Phase 1)	Datang Power Ximeng lignite tail coal (ash 44%, ~2800 kcal) upgraded to 5500 kcal	2018 pilot test
Quality Improvement (Phase 2)	Ximeng lignite (original sample >4000 kcal) upgraded to >6000 kcal, reaching ordinary steam coal standard	2023 sample test
Cost Advantage	Production cost approx. 1/2–1/3 of heavy medium method and flotation method; pre-combustion ash-sulfur removal cost approx. 1/7–1/10 of power plant wet limestone flue gas desulfurization	Technical report
Applicable Particle Size	13 mm–200 mesh fine coal and tail coal slime can use dry primary tailing discarding	Technical report

This set of data shows that physical-field separation technology has already run through the complete chain of source quality improvement — reduction — resource utilization on coal, the most typical bulk material, and its methodology has a solid technical foundation for migration to metallic and non-metallic ores.

(II) Geopolymer Cementitious Material: Calcination-Free, Solid-Waste-Based Low-Carbon Cementing System

Geopolymer is the exit of the coupling system. Its raw material broad-spectrum nature determines how many types of solid waste it can consume, and its network structure determines how firmly it can lock pollutants.

1. Reaction Mechanism: From Alumino-Silicate Raw Materials to Three-Dimensional Network

Geopolymer was first discovered and named by French scientist Joseph Davidovits in the 1970s, initially prepared from kaolin through alkali activation reaction. Its formation process can be summarized into three core stages:

1. **Dissolution stage:** Under the action of strong alkali activator (such as NaOH, water glass), the silico-aluminate glass phase in solid waste undergoes Si-O and Al-O bond cleavage, dissociating active silicon and aluminum ions;
2. **Monomer reconstruction stage:** The dissociated silicon and aluminum ions recombine to form oligomeric silicon-oxygen tetrahedra and aluminum-oxygen tetrahedra monomers;
3. **Polycondensation stage:** Oligomeric monomers condense by sharing oxygen atoms to form a three-dimensional network inorganic polymer structure, with alkali metal ions (Na^+ , K^+) participating in charge balance and skeleton construction.

The finally formed N-A-S-H (sodium aluminosilicate hydrate) or N-S-H reticulated gel is the key phase responsible for mechanical load bearing and pollutant immobilization. It is precisely this three-dimensional network structure that endows geopolymer with a series of unique properties distinct from traditional cement.

2. Raw Material End Broad-Spectrum Nature: Natural Compatibility with Solid Waste Categories

Geopolymer raw materials are materials rich in silicon and aluminum and with reactive activity. With deepening research, the raw material scope has expanded from natural minerals such as kaolin and volcanic pumice to fly ash, coal gangue, slag, steel slag, manganese slag, red mud, various tailings, construction waste dust

and other industrial solid wastes, achieving treating waste with waste. This highly matches the solid waste spectrum of the mining-processing-metallurgy industry:

Mining-Processing-Metallurgy Solid Waste	Main Chemical Composition	Compatibility as Geopolymer Raw Material
Coal gangue	SiO ₂ 45%–69%, Al ₂ O ₃ 12%–39%	High alumino-silicate, suitable as corrective material and main raw material
Fly ash	SiO ₂ , Al ₂ O ₃ , FeO, Fe ₂ O ₃ , CaO	Classic geopolymer raw material, good activity
Blast furnace water slag (GGBS)	Silicate glassy phase	Provides calcium source, accelerates reaction, improves early strength
Steel slag	Calcium-iron silicate containing	Provides calcium source and aggregate function
Various tailings	Depends on mineral type, mostly alumino-silicate containing	Can be used as aggregate or raw material after activation
Smelting slag (copper slag, lead-zinc slag, etc.)	Iron silicate containing, low Ca, Al and glass phase content	Requires alkali activation, but its heavy metal self-cementation immobilization performance is outstanding
Red mud	High alkali, iron-aluminum containing	Can be used synergistically with slag and fly ash

It is particularly worth noting that although non-ferrous metallurgical slag has low potential cementitious activity — its Ca, Al element content and glass phase content are generally lower than water-quenched blast furnace slag — its heavy metal self-cementation and immobilization performance is very outstanding, which is precisely the function most needed in the metallurgy stage.

3. Performance Characteristics: Four Indicators Comprehensively Superior to Traditional Cement

(1) Carbon emissions and energy consumption. No high-temperature calcination, production process can reduce CO₂ emissions by approximately 80% compared with traditional cement. This is of strategic significance under the dual carbon goals — cement industry carbon emissions account for approximately 7%–8% of global anthropogenic greenhouse gas emissions, and the geopolymer route fundamentally avoids limestone decomposition, the main carbon source.

(2) Mechanical properties. Early strength and rapid hardening characteristics are significant: fly ash-based geopolymer 28-day compressive strength can reach 55.6–136 MPa; smelting reduction slag-based geopolymer 28-day compressive strength reaches 93.4 MPa; under 20 °C curing for 28 days, geopolymer compressive strength is approximately 69 MPa, while ordinary Portland cement is approximately 46 MPa. Using low-silicon iron tailings as the main raw material and metakaolin as alumino-silicate corrective material, under conditions of Si/Al molar ratio 2.75, liquid/solid ratio 0.30, alkali activator modulus 1.4, and room-temperature bag-sealed curing, the prepared geopolymer 28-day strength reached 72.3 MPa.

(3) High temperature resistance and volume stability. Does not decompose at 1000–1200 °C high temperature; 400 °C linear shrinkage is only 0.1%, 800 °C linear shrinkage is 0.2%–2%, and it can retain over 60% of original strength, significantly superior to traditional cement.

(4) Corrosion resistance and impermeability. Sulfate erosion resistant; in 5% sulfuric acid solution, decomposition rate is only 1/12 of Portland cement, and acid corrosion resistance is approximately 5 times that of ordinary Portland

cement; dense structure with excellent impermeability and freeze-thaw cycle resistance.

(5) Heavy metal immobilization capacity. This is the performance of geopolymer most compatible with mining-processing-metallurgy scenarios. The immobilization mechanisms of alkali-activated geopolymer gel for heavy metals include three categories: electrostatic adsorption, physical encapsulation, and formation of stable compounds. Measured data shows:

- When using fly ash and metakaolin as raw materials, when $\text{Pb}(\text{NO}_3)_2$ addition is less than 5%, over 99.5% of lead is immobilized in the cementitious material, and lead concentration in leachate is less than 5 mg/L;
- Lead-zinc ore slag using Na_2O as alkali activation material to prepare cementitious material, tested by HJ/T 299—2007 sulfuric acid-nitric acid method, the leachate concentrations of zinc, chromium and lead decreased from 183.10, 7.66, and 26.13 mg/L in the original slag to 0.84, 0.07, and 0.12 mg/L respectively, with heavy metal immobilization efficiency exceeding 90%;
- Copper slag/fly ash geopolymer system has immobilization rates of over 99% for all five heavy metals: Cr^{3+} , Ni^{2+} , Cd^{2+} , Pb^{2+} , Cu^{2+} ;
- Alkali-activated lead-zinc smelting slag immobilizing chromium slag, Cr immobilization efficiency exceeds 95%, 28-day compressive strength is 28.35 MPa, and leachate concentrations are all below the 5 mg/L safety limit.

4. Client's Technical Accumulation in Geopolymer Direction

Huzhu Green Building's silicon-based nano-cementitious material technology is an originally developed new inorganic nano-cementitious material system, which can replace traditional cement for concrete, grouting materials, floor materials, etc., achieving high performance of solid waste-based building materials. This technology was awarded the 2024 Cement Grinding System Best Available Technology (BAT) title at the 16th Domestic and International Cement Grinding

New Technology Exchange Conference and Exhibition co-hosted by 20 provincial (municipal) silicate societies in May 2024.

The supporting solid waste harmless stabilization technology targets industrial solid waste containing heavy metals and toxic and harmful elements, develops special cementitious solidification materials, can effectively immobilize pollutants such as thallium and beryllium, with immobilization rate over 99%, thoroughly eliminating environmental risks while achieving resource utilization.

Representative patent achievements include:

- **A physical adhesive for refractory recombined stone and its preparation method and application (CN118026709B):** achieves 100% resource utilization of solid waste such as coal gangue, and is the company's core exclusive technology;
- **A cementitious material for solidifying lepidolite slag and its preparation method and application:** stably immobilizes over 99% of toxic harmful elements in lepidolite slag, preparing high value-added green building materials;
- **Steel slag-based two-component high-strength grouting material (CN113636820B):** prepares high-performance grouting material using steel slag as main raw material;
- **Cement-free solid waste-based concrete formulation for PHC pipe piles and its preparation method:** solid waste-based concrete technology that completely replaces cement.

III. Internal Logic of Coupling: Bidirectional Closure of a Material Flow

Physical-field mineral processing technology and geopolymer cementitious material belong to two seemingly different technical directions of separation and

cementation, but when they are examined within the entire mining-processing-metallurgy flow, it is found that their interface is naturally compatible. The following explains one by one from three dimensions: material flow, cost-energy flow, and environmental risk.

(I) Material Flow Coupling: Every Material Stream Has a Corresponding Outlet

In the traditional flow, physical sorting only undertakes the single task of selecting concentrate, and everything else becomes tailings; geopolymer only passively consumes solid waste in building material scenarios. In the coupling system, physical-field sorting actively disassembles materials into three types, and geopolymer provides outlets for each type:

Material Streams from Physical-Field Sorting	Characteristics	Geopolymer/Cementitious System Disposal Outlet
High-grade valuable concentrate	Metal enriched	Enters smelting process, increases feed grade, reduces slag volume
Medium-grade construction-materializable aggregate/sand-gravel	Coarser particle size, stable composition	Directly as construction sand-gravel, underground backfill aggregate
Fine active alumino-silicate material (tailings micro powder, waste rock powder)	Rich in alumino-silicate, large specific surface area	As geopolymer cementitious material raw material or active admixture
Heavy metal enriched phase	Pollutants concentrated	Solidified by geopolymer cementitious network, leachate concentration far below limits

The key significance of this disassembly lies in: physical-field sorting transforms mixed pollution into classified resources. In the mixed state, heavy metals in tailings contaminate the entire material body; once the heavy metal enriched phase is separated through physical fields and directionally solidified, the

remaining materials can enter building material and backfill channels without barriers. Separation is the prerequisite for resource utilization, and cementation is the landing point of separation.

Taking the practice of Shuikoushan Nonferrous as an example: the processing stage adopts intelligent sorting process to pre-discard part of low-grade waste rock, with annual waste rock output of 95,000 tons all comprehensively utilized as building material raw materials; adopts concentration and filtration process to reduce tailings slurry moisture content below 15% to form dry tailings sand, with annual output of 200,000 tons directly sold to building material manufacturers; the remaining tailings are backfilled into underground goaf in the form of high-concentration paste backfill. Three outlets operate in parallel, achieving zero discharge from tailings pond and 100% wastewater recycling.

(II) Cost and Energy Coupling: Cost Reduction at Both Ends Simultaneously

The coupling system forms a double reduction effect in cost structure.

Cost reduction on the processing side comes from reduction. Physical-field pre-concentration discards 30%–50% of ineffective processing volume at the coarse particle stage, directly reducing electricity, water and steel consumption in grinding, flotation, concentration and conveying steps.

Practice data from more than 30 low-grade iron mines shows that subsequent whole-process energy, water and steel consumption can be reduced by approximately 40%.

Cost reduction on the backfilling side comes from substitution. Cemented backfilling cost can account for 20% of total mining cost, of which cement cost accounts for approximately 75% of cemented backfilling cost. This means

cementitious materials are the absolute majority of backfilling cost. After replacing cement with geopolymers-based low-carbon cementitious material:

- The new low-carbon cementitious material of a Tongling Nonferrous subsidiary has a dosage of approximately 60%–70% of Portland cement under equivalent conditions, reducing mine backfilling cost by about one-third;
- Shishudi Gold Mine low-carbon solid waste cementitious material replacing cement, saves over 50% of cementitious material, increases tailings utilization by over 10%, reduces backfilling cost by over 30%, and reduces carbon emissions by 90%;
- Tianxing Iron Mine new cementitious material achieves 28-day uniaxial compressive strength of 3.14 MPa under cement-sand ratio of 1:10, superior to ordinary Portland cement and slag powder, reducing annual backfilling cost by approximately 13 million yuan.

The superposition of cost reduction at both ends, plus policy dividends of resource tax reduction (tailings reduction 50% or exemption, backfill mining replacement coal resource tax reduction 50%) and product revenue included at 90% for taxable income, means the economic viability of the coupling system has already crossed the break-even point.

(III) Environmental Risk Coupling: Transforming Mobile Pollution into Stable Solidification

The most intractable environmental risk of mining-processing-metallurgy solid waste comes from the mobility of heavy metals and toxic and harmful elements. Tailings pond leakage, waste rock yard leaching, and smelting slag scattering are essentially all pollutants moving. The coupling system blocks this risk simultaneously from two directions.

First, physical-field separation concentrates pollutants into a controllable small amount of material. Through magnetic separation, electrical separation

and other physical means to separate heavy metal enriched phases, the treatment scale of pollutants is reduced from 10,000-ton level to 100-ton level, greatly reducing solidification cost.

Second, the geopolymer cementitious network permanently locks pollutants. Geopolymer gel immobilizes heavy metals through three paths: electrostatic adsorption, physical encapsulation, and formation of stable compounds, with leachate concentration reducible to below one-tenth of the limit. Measured data from iron tailings alkali-activated solidification system shows that heavy metal leaching can be reduced by up to 95%; meanwhile, compared with Portland cement, environmental impact (global warming potential and energy consumption) is reduced by approximately 35%.

More notably, aluminosilicate mineral phases are abundant in natural rocks. Geopolymer solidified products are chemically homologous to geological minerals, and their long-term stability is far higher than that of Portland cement systems relying on calcium silicate hydrate — this is the underlying logic of solving environmental problems with geological methods.

(IV) System-Level Coupling Schematic

Combining the above three dimensions, the whole-process material flow of the coupling system can be understood item by item by stage in the following table:

Stage	Physical-Field Sorting Action	Output Material Streams	Geopolymer/Cementitious System Outlet
Mining	Large dry magnetic separation, XRT intelligent sorting	Valuable ore → processing; waste rock → three material types	Waste rock as construction aggregate, underground backfill aggregate, active powder raw material

Processing	Magnetic/gravity/electrical/multi-field synergistic cleaning	Concentrate → smelting; middling and coarse tailings → aggregate; fine tailings micro powder → cementitious raw material	Fine tailings as main raw material for geopolymer cementitious material; zero tailings pond discharge becomes possible
Metallurgy	Magnetic separation recovering scrap steel, electrical separation recovering valuable metals	Valuable metals → furnace return; smelting slag, dust → auxiliary materials	Smelting slag as calcium source and heavy metal immobilization carrier, dust co-solidified
End-stage	—	Backfill body, green building materials, functional materials	Returns to mine and engineering site, material closed loop formed

IV. Coupled Application Analysis in Mining Stage

The mining stage is the first gate of the coupling system. The root cause of solid waste problems in this stage is dilution — the more wall rock is mixed in, the greater the ineffective load of all subsequent stages. Therefore, completing separation at the mining end is the action with the highest cost-performance in the entire closed loop.

(I) Pain Points

Taking quartz vein-type tungsten ore as an example, the ore vein is thin and steeply inclined, with high wall rock mixing rate during mining, and ore dilution rate can reach up to 90%. Once wall rock is mixed in, it must go through the entire process of crushing, grinding and separation together with the ore, not only pushing up costs but also diluting the feed grade and reducing mineral processing recovery. Meanwhile, the promotion of medium-deep hole blasting method, while improving mining efficiency, further aggravates ore dilution.

(II) Entry Point of Physical-Field Technology: Moving Sorting Action Forward to Mining

(1) Large dry magnetic separation pre-concentration. Dry magnetic separation of large ore after primary crushing and before secondary crushing directly discards wall rock. Application practice in the four major Panxi mining areas (Panzhihua, Baima, Hongge, Taihe) shows that large dry magnetic separation technology has very significant effects in reducing mining dilution rate and improving ore recovery rate.

(2) XRT intelligent photoelectric pre-concentration. X-ray transmission or high-definition visual recognition is used at 10–80 mm coarse particle size to accurately identify and discard waste rock. Dajishan Tungsten Mine Processing Plant adopted the combined process of manual hand sorting (+80 mm) + XRT pre-concentration (-80+16 mm). The average annual waste rock sorting rate in 2021 was 52.87%, and ore qualification rate was 92.77%.

(3) Water saving value of dry pre-concentration. For water-deficient mining areas, dry magnetic separation pre-concentration can save over 90% of water compared with wet method, which not only reduces water cost and new water

intake quota pressure, but also avoids fine tailings and wastewater treatment problems brought by wet processes.

(III) Continuation of Geopolymer Material: Three Outlets for Waste Rock

Waste rock discarded by physical pre-concentration is no longer waste in the coupling system, but raw materials for three product lines.

Outlet 1: Directly as construction sand and gravel aggregate. Waste rock with stable composition and suitable particle size can be used as qualified construction sand and gravel after screening and shaping, achieving that ore is product upon extraction. Liaoning Wengquangou Boron-Iron Mine optimized the post-processing process flow, processed tailings into qualified construction sand and gravel and brought them to the market, which not only alleviated the tight capacity pressure of tailings ponds, but also transformed industrial by-products into marketable products.

Outlet 2: As underground backfill aggregate. This is the most direct in-situ consumption path for waste rock. Waste rock is mixed with fine tailings and geopolymer cementitious material to make backfill slurry or paste to backfill goaf, which not only consumes solid waste, but also controls ground pressure activities, prevents surface subsidence, and improves ore recovery rate — after Xintianling Tungsten built the tailings paste backfill system, resource recovery rate increased by over 10%. Jinchuan Group's full tailings + paste backfill technology makes approximately 200,000 tons of tailings into paste annually for safe backfill goaf, achieving in-situ recycling of resources.

Outlet 3: Processed into active powder raw material. Waste rock fine powder can be used as alumino-silicate raw material or active admixture for geopolymer cementitious material after grinding and activation. This path

transforms low-value waste rock into high-value material components, and is the key channel for high-value utilization.

(IV) Coupling Effects

Indicator	Traditional Mode	Coupled Mode	Improvement Source
Mining dilution rate	High (up to 90% for tungsten ore)	Significantly reduced	Large dry magnetic separation pre-concentration
Mill feed volume	100%	Reduced by 30%–50%	XRT/photoelectric pre-concentration waste discarding
Processing freshwater consumption	Baseline	Reduced by 90%+ (dry pre-concentration)	Dry magnetic separation technology
Waste rock destination	Waste rock yard stockpiling	Building material/backfill/active powder	Geopolymer cementitious system
Resource recovery rate	Baseline	Increased by 10%+	Backfill mining method + paste backfill

V. Coupled Application Analysis in Processing Stage

The processing stage is the stage with the largest solid waste generation, and also the main battlefield where the coupling system truly exerts scale benefits. There are two key propositions in this stage: recovering fine-grained valuable components, and sending out fine tailings at scale.

(I) Pain Points

The processing stage is the stage with the largest solid waste generation, and also the stage with the most concentrated resource waste. Three structural problems are particularly prominent.

First, fine-grained materials are difficult to recover. Traditional flotation machines have difficulty effectively recovering fine minerals below 20 μm ; fine ilmenite (-0.019 mm) lacks effective separation methods, leading to loss of large amounts of valuable components with tailings.

Second, low utilization rate of co-associated components. Multi-element paragenesis is a typical feature of many deposits in China. Limited by traditional processing-metallurgy technical conditions, in the past most mines could only efficiently recover 12 types of main minerals, and a large number of associated components with strategic value were lost with tailings, forming hidden resource loss.

Third, tailings are fine-grained, large in volume and high in disposal cost. Fine tailings not only occupy storage capacity and increase safety risks, but also have high dehydration, conveying and stockpiling costs.

(II) Entry Point of Physical-Field Technology: Quality-Differentiated Sorting and Deep Purification

(1) Composite force field equipment improves fine particle recovery. The suspension-vibrating cone concentrator is suitable for sorting 0.100–0.005 mm slime; the SSS type wet double-frequency double-vertical-ring high-gradient magnetic separator can efficiently recover -0.020 mm fine ilmenite, with concentrate grade and recovery rate increased by 6.71% and 9.68% respectively compared with conventional high-gradient magnetic separators; centrifugal high-gradient magnetic separators can be widely used for fine-

grained magnetic ore separation. The common feature of these devices is to expand the separation window with composite force fields, pulling fine-grained valuable minerals that originally entered tailings back into the product flow.

(2) Multi-physical-field synergy for deep purification. In high-purity quartz sand preparation, collaborative application of magnetic field, microwave field, ultrasonic field, temperature field and pressure field has made progress: microwave selective heating and micro-explosion effects promote inclusion impurity liberation, ultrasonic cavitation effect strengthens interfacial reactions and impurity peeling, temperature-pressure field induces polymorphic phase transformation and lattice reconstruction, achieving selective migration of impurities. This multi-field synergy approach is also an important direction for processing complex refractory metal ores and solid waste purification.

(3) Quality-differentiated sorting, optimal use of superior materials. The practice of Hubei Xingfa Shukongping Phosphate Mine is highly valuable for reference: based on the 1.2 million tons/year heavy medium processing project, a complete mineral material graded utilization system was built — high-grade lump ore is directionally supplied to the fine phosphorus chemical industry, medium-low grade ore is processed for wet-process phosphoric acid production, and by-product fine ore from mining is processed into phosphate compound fertilizer and feed calcium products, allowing different grades of ore to have their appropriate place, with every portion of resource matched to suitable downstream application scenarios. The mine also lowered the feed size lower limit from 3 mm to 1 mm, successfully releasing tens of millions of tons of dormant phosphate ore resources.

(III) Continuation of Geopolymer Material: Large-Scale Outlet for Fine Tailings

Fine tailings are the main body of processing solid waste, and also the part most difficult to consume through traditional building material channels. Geopolymer cementitious material precisely provides a large-scale outlet for this type of material.

(1) Underground cemented backfill — the largest-volume outlet. Using fine tailings as aggregate and geopolymer cementitious material as binder to prepare backfill slurry can consume extremely large-scale tailings. Measured data shows that low-carbon solid waste cementitious material prepared with slag powder, steel slag powder and F-gypsum as main raw materials, when using gold tailings as aggregate, under the premise of achieving the same technical indicators, can save over 50% of cementitious material, increase tailings utilization by over 10%, reduce backfilling cost by over 30%, and reduce carbon emissions by 90%. Tongling Nonferrous low-carbon cementitious material collaboratively disposed of 10 million tons of mine tailings in three years, fully proving its large-scale consumption capacity.

(2) Tailings-based geopolymer building materials. Low-silicon iron tailings with added metakaolin as alumino-silicate corrective material, under composite alkali activation of NaOH and water glass, 28-day strength can reach 72.3 MPa. There are large amounts of amorphous N-A-S-H and C-S-H gel phases inside the specimen, tightly cementing mineral crystals and filling particle pores, forming a dense overall structure. This type of material can be directly used for brick making, blocks, pavement materials, grouting materials, etc.

(3) Tailings solidification and stockpiling and surface cover. For tailings that temporarily do not have large-scale utilization conditions, geopolymer

cementitious material can be used for solidification treatment. Using phosphorus slag-based geopolymer cementitious material to solidify 65% fine tailings slurry, with cementitious material dosage of 3% (mass fraction), the tailings solidified body compressive strength can reach 0.2 MPa after 28 days of solidification, meeting tailings solidification and stockpiling requirements. Geopolymer stabilization research on mine tailings shows that under 30%–50% binder dosage, stable microstructure can be obtained and heavy metals can be effectively immobilized, suitable for both mine backfill and surface cover scenarios.

(4) Tailings reprocessing and value addition. For historically stockpiled tailings, physical-field technology can carry out secondary recovery. Panxi Hongge Vanadium-Titanium Magnetite Mine continuously carried out technical transformation for iron-titanium resource re-recovery from tailings. After the project was put into operation, TiO_2 grade in tailings dropped below 4%, and annually newly added titanium concentrate 50,000 tons and iron concentrate 21,700 tons were recovered from tailings. After the ultra-fine ilmenite enhanced recovery project was completed and put into operation, it revitalized nearly 87 million tons of titanium resources, equivalent to newly proven 3 super-large titanium mines. This type of practice shows that the tailings pond itself is an above-ground mine, only requiring suitable sorting technology and economically feasible recovery window.

(IV) Coupling Effects

Indicator	Traditional Mode	Coupled Mode	Improvement Source
Fine valuable mineral recovery	Massive loss	Composite force field equipment effective recovery	High-gradient magnetic separation, suspension-

			vibrating cone concentrator
Tailings destination	Tailings pond stockpiling	Backfill/building material/solidified stockpiling/reprocessing	Geopolymer cementitious system
Tailings pond discharge	Continuous pond inflow	Zero discharge achievable	Full-volume resource utilization + one mine one policy cementitious scheme
Tailings pond service life	Continuously shortening	Extended by 5–6 years	Tailings comprehensive utilization rate improved
Associated metal recovery	Lost with tailings	Large-scale recovery	Quality-differentiated sorting + deep purification

VI. Coupled Application Analysis in Metallurgy Stage

The solid waste characteristics of the metallurgy stage are large slag volume, complex composition and high environmental risk, which is also the scenario where the self-cementation and solidification advantages of geopolymer materials are best demonstrated. This stage is also the main battlefield for internal collaborative utilization of hazardous waste.

(I) Pain Points

The solid waste characteristics of the metallurgy stage are large slag volume, complex composition and high environmental risk. Each ton of pig iron smelted produces 0.3–0.9 tons of blast furnace slag, each ton of steel produced discharges 0.1–0.3 tons of steel slag, and each ton of alumina produces 0.6–2 tons of red mud. Non-ferrous metallurgical slag has many types, complex composition, large

structural differences and low pozzolanic activity — its Ca, Al element content and glass phase content are generally lower than water-quenched blast furnace slag, which is the essential reason for the low potential cementitious activity of non-ferrous metallurgical slag.

More intractable is hazardous waste. If hazardous wastes such as lead-containing materials, silver dross, white smoke dust, and anode slime cannot be internally collaboratively utilized, they can only be disposed of externally, with high cost, high risk, and massive loss of resource value.

(II) Entry Point of Physical-Field Technology: Recovery of Valuable Components in Slag and Reduction of Hazardous Waste

(1) Recovering metals from slag. Magnetic separation can be used to recover scrap steel from steel slag produced in smelting; electrical separation can be used to recover useful metals such as copper and aluminum from solid waste. Physical mineral processing processes (magnetic separation, gravity separation) for industrial waste have the advantages of low energy consumption and low pollution, and have become an important means in the field of resource recovery and environmental protection.

(2) Physical pre-treatment and enrichment of hazardous waste. For hazardous waste materials with complex composition, physical-field sorting can achieve pre-enrichment of valuable components and concentration of pollutant phases, providing higher-grade and more uniform raw materials for subsequent metallurgical treatment, while reducing the total amount of material entering the disposal stage.

(III) Continuation of Geopolymer Materials: Self-Cementation

Advantage of Smelting Slag

The performance of metallurgical slag in the geopolymer system is the biggest highlight of the coupling system in the metallurgy stage.

(1) High heavy metal immobilization rate and good stability. After lead-zinc ore slag using Na_2O as alkali activation material to prepare cementitious material, zinc, chromium and lead leachate concentrations decreased from 183.10, 7.66, and 26.13 mg/L to 0.84, 0.07, and 0.12 mg/L respectively, with immobilization efficiency exceeding 90%. Copper slag/fly ash geopolymer has immobilization rates of over 99% for all five heavy metals: Cr^{3+} , Ni^{2+} , Cd^{2+} , Pb^{2+} , Cu^{2+} , with copper showing the best immobilization effect.

(2) Clear solidification mechanism. Studies have shown that Zn^{2+} and Pb^{2+} participate in the formation of geopolymer structure and replace the positions of Ca^{2+} or Na^+ , thus being chemically solidified in the geopolymer framework system; while Cu, Pb, Cr and other elements participate less in hydration reactions, and are mainly physically preserved in the cemented body. C-S-H gel has significantly better physical solidification effect on copper and chromium than zinc. This dual chemical + physical solidification mechanism is the unique advantage of geopolymer in treating smelting slag.

(3) Strength meets building material requirements. Using copper slag and fly ash as main raw materials, under conditions of copper slag dosage 20%, alkali activator addition 25%, water glass modulus 1.2, and 80 °C curing for 12 h, geopolymer 28-day compressive strength reaches 47.53 MPa. The alkali-activated lead-zinc smelting slag immobilizing chromium slag system, with chromium slag dosage 30%, has 28-day compressive strength of 28.35 MPa, meeting the 10 MPa strength requirement for building materials.

(4) Collaborative utilization of steel slag and slag. Steel slag and slag, as calcium sources, can accelerate geopolymer reaction kinetics, improving early strength and long-term durability. Using steel slag, fly ash plus a certain amount of alkali activator to prepare geopolymer cementitious material, and iron ore tailings as aggregate, when tailings addition is 50%–55%, non-fired products with 3-day strength all above 10 MPa can be prepared.

(IV) Internal Collaborative Utilization of Hazardous Waste:

Industrial-Level Zero-Waste Group Practice

The value of the geopolymer cementitious system in the metallurgy stage is not only reflected in slag treatment, but also in internal collaborative utilization of hazardous waste.

Hunan Nonferrous, as one of the first batch of zero-waste group pilots in Hunan Province, established internal direct supply channels for smelting slag, hazardous waste utilization sharing center, and solid waste full lifecycle intelligent management and control platform, achieving cross-enterprise and cross-stage collaborative utilization of solid waste within the Shuikoushan copper-lead-zinc industrial base. The solid waste recycling rate increased from less than 30% to 90%; in 2025, it internally collaboratively utilized 14 types of hazardous waste with a total volume of 67,000 tons, creating annual benefits of over 100 million yuan.

The specific practices of Shuikoushan Nonferrous are also noteworthy: establishing an internal sharing center for lead-containing hazardous waste utilization facilities, cumulatively receiving 57,470 tons of lead-containing materials, among which lead slag, silver dross, converting white smoke dust, copper anode slime leaching residue, etc. respectively enter bottom-blown furnaces and side-blown furnaces for crude lead smelting and precious metal recovery, achieving full-volume resource utilization of hazardous waste.

These practices show that the zero-waste goal of the metallurgy stage can be achieved through the trinity path of physical-field sorting and purification + cementitious system stable solidification + intra-group collaborative configuration.

(V) Coupling Effects

Indicator	Traditional Mode	Coupled Mode	Improvement Source
Smelting slag destination	Stockpiling/low-value external sale	Cementitious material raw material/building material	Geopolymer alkali activation
Heavy metal leachate concentration	High (e.g., lead-zinc slag zinc 183.10 mg/L)	Reduced to 0.84 mg/L	Geopolymer chemical + physical immobilization
Heavy metal immobilization rate	—	90%–99%+	Three-dimensional network locking
Solid waste recycling rate	Less than 30%	Increased to 90%	Internal collaboration + cementitious utilization
Hazardous waste disposal	External disposal, high cost	Internal shared utilization, annual benefit over 100 million yuan	Hazardous waste sharing center

VII. Comprehensive Benefit Analysis

The value of the coupling system needs to be reflected on an accountable ledger. The following summarizes publicly available quantitative data from four dimensions: environment, economy, safety, and resources, for project calculation and decision-making reference.

(I) Environmental Benefits

Benefit Item	Quantitative Data	Source Scenario
CO ₂ Reduction	Cementitious material production reduced by approx. 80% vs. traditional cement	Geopolymer preparation
Carbon Emission Reduction	Backfill stage carbon emissions reduced by 90%	Gold tailings backfill
Total Carbon Reduction	Carbon emissions reduced by nearly 1.3917 million tons in three years	Tongling Nonferrous low-carbon cementitious material
Environmental Impact Reduction	Global warming potential and energy consumption reduced by approx. 35% vs. Portland cement	Iron tailings alkali-activated solidification
Heavy Metal Leaching Reduction	Up to 95%	Iron tailings GGBFS solidification system
Wastewater Recycling	100% recycling, tailings pond zero discharge	Shuikoushan Kangjiawan Mine
Water Saving	Dry pre-concentration saves 90%+ water vs. wet method	Magnetite dry magnetic separation

(II) Economic Benefits

Benefit Item	Quantitative Data
Cementitious Material Substitution Cost Reduction	Dosage approx. 60%–70% of cement, backfill cost reduction approx. 1/3
Cementitious Material Saving	Over 50% (Shishudi Gold Mine)
Backfill Cost Reduction	Over 30%; annual backfill cost reduction approx. 13 million yuan (Tianxing Iron Mine)
Tailings Pond Cost Saving	Annual cost saving over 25 million yuan (Anhui Development Mining)

Tailings Comprehensive Utilization Benefit	Waste rock 95,000 t/yr + dry tailings sand 200,000 t/yr, direct economic benefit 5.65 million yuan
Tailings Reprocessing Value Addition	Annual new titanium concentrate 50,000 t, iron concentrate 21,700 t
Hazardous Waste Internal Utilization Benefit	Annual benefit over 100 million yuan (Hunan Nonferrous)
Tax Reduction/Exemption	Tailings resource tax exemption/reduction, backfill replacement coal reduction 50%, product revenue included at 90%
Resource Tax Reduction Case	A mining company's resource tax reduced from over 1.88 million yuan in 2021 to 94,000 yuan in H1 2026

(III) Safety Benefits

- **Eliminate tailings pond risk:** Anhui Development Mining tailings pond achieved zero discharge for consecutive months, resolving tailings pond environmental and safety risks from the source; Shuikoushan Kangjiawan Mine technical upgrade project has not discharged tailings to the tailings pond since commissioning, reducing dam safety risk.
- **Control ground pressure activities:** Tailings sand used for underground backfill effectively controls ground pressure activities, reduces underground goaf safety risks, and improves mine production efficiency.
- **Extend mine life:** Xintianling Tungsten tailings comprehensive utilization rate exceeds 60%, cumulatively reducing tailings sand entering the pond by approximately 3.7 million tons, extending tailings pond service life by 5–6 years; intelligent backfill system reduces resource mining risks around mine pillars, extending mine lifecycle.
- **Reduce transportation risks:** Tongling Nonferrous built over 10 km of tailings conveying pipelines, conveying excess tailings sand through

pipelines for ecological backfill restoration, replacing vehicle transportation and reducing dust and traffic safety hazards.

(IV) Resource Benefits

- **Improve comprehensive resource utilization rate:** Lomon Panzhihua Mineral Products Co., Ltd. independently developed titanium separation collector, increasing titanium resource comprehensive utilization rate to 45%, significantly higher than the Panxi regional industry average of 29%; after sulfur-cobalt concentrate recovery technical transformation was implemented, scattered metals such as cobalt, nickel and copper achieved large-scale recovery.
- **Revitalize dormant resources:** Shukongping Phosphate Mine lowered the feed size lower limit from 3 mm to 1 mm, releasing tens of millions of tons of dormant phosphate ore resources; Panxi Hongge ultra-fine ilmenite enhanced recovery project revitalized nearly 87 million tons of titanium resources.
- **Forming above-ground mines:** tailings re-recovery turns historically stockpiled tailings ponds into above-ground mines with continuous resource output.
- **Extend industrial chain:** Prepare new building materials from tailings, achieving transformation from traditional mining to new materials industry.

VIII. Practical Foundation and Industrialization Conditions

Whether a technical path can be promoted depends on three conditions: whether the technical supply is complete, whether industrialization carriers are available, and whether the industry already has comparable successful cases. The following explains the current actual status item by item.

(I) Technical Supply Side: Complete Technical System

Huzhu Green Building (Beijing) Technology Co., Ltd. was founded in June 2010, and is a national high-tech enterprise, national innovative SME and technology-based SME specializing in the field of bulk industrial solid waste resource comprehensive utilization. Relying on research platforms of professional academic institutions such as the National Building Materials Institute and the Chinese Academy of Geological Sciences, the company has achieved multiple breakthrough results in key technical fields such as physical method material separation, new silicon-based nano-cementitious materials, and dry nano-grinding. Its technical system highly corresponds to the coupling path proposed in this report:

Capability Required by Coupling System	Huzhu Green Building Corresponding Technology	Key Indicators
Physical-Field Separation and Purification	Physical method material separation technology (magnetic-gravity-acoustic-electrical-optical multi-physical-field impurity removal)	No chemical reagents needed; 3T gathered-magnet permanent-magnet high-intensity magnetic, field strength 2.8-3.0 T, rated international advanced level
Cementation and Building Materialization	Silicon-based nano-cementitious material technology	Can replace cement; 2024 Cement Grinding System Best Available Technology (BAT)
Pollutant Immobilization	Solid waste harmless stabilization technology	Immobilizes pollutants such as thallium and beryllium, immobilization rate over 99%
Category Coverage	Covers coal gangue, steel slag, water slag, coal gasification slag, lepidolite slag, red mud, industrial waste gypsum, various tailings	All can achieve 100% resource utilization

The company cumulatively owns 23 patented technologies of various types, with a high proportion of invention patents, covering multiple technical directions such as solid waste sorting, cementitious materials, green building materials, and special equipment. As the vice-chairman unit of the National Metallurgical Slag Professional Committee, the company continuously conducts technical research and industrialization application in the field of solid waste resource utilization such as tailings waste rock, coal-based solid waste, and smelting slag.

(II) Industrialization Carrier: Replicable Implementation Model

China Industrial Solid Waste Management Co., Ltd. (CIWM), as the global technology industrialization operation platform of Huzhu Green Building, takes collaborative development of technology + capital + industry as its strategy. Its scientific research base is located in Nanchang Economic and Technological Development Zone, Jiangxi Province. It has established R&D bases and pilot plants in Nanchang, Jiangxi and Baotou, Inner Mongolia, and has laid out solid waste resource utilization projects in 27 provinces and regions including Inner Mongolia, Jiangxi, Shanxi, Shaanxi, Hebei, Yunnan, Sichuan, Heilongjiang, etc., forming an industrial network covering key waste-generating regions nationwide. Key demonstration projects include:

- **Baotou Hongjing Coal-Based Solid Waste Sorting and Utilization Project:** planned construction includes 4 production workshops: magnetic-gravity-optical impurity removal workshop, kaolin production workshop, clean coal production workshop, and mineral soil conditioner production workshop, with supporting public works and auxiliary facilities. After completion, it will become Baotou's first full-industrial-chain solid waste treatment benchmark project;
- **Shanxi Shanyin County annual processing million-ton-level coal gangue comprehensive utilization project:** the company undertakes coal gangue

and other solid waste quality improvement with the world-leading 3T permanent magnet + silicon-based gel technology route. Construction started on April 15, 2025, and this project was named Shanyin Model by relevant departments of UNEP;

The company has signed strategic investment framework agreements with multiple regions including Jidong District People's Government of Jixi City and Yichun City People's Government, with total contracted amount of 6.62 billion yuan, and won bids for multiple million-ton-class industrial solid waste resource utilization projects.

(III) Industry Practice Verification: Multiple Comparable Successful Cases

The coupling path proposed in this report has already had multiple stage-wise verifications within the industry:

Practice Entity	Core Approach	Key Results
China Minmetals	Mining-Processing-Metallurgy-Waste integrated layout, 5F+Dual Cycle model	Three-dimensional efforts: plant internal circulation, group internal circulation, social external circulation
Anhui Development Mining	Full tailings sand recycling utilization system	Tailings comprehensive utilization rate 91.61%–98.33%, consecutive months of tailings pond zero discharge, annual cost saving over 25 million yuan
Xintianling Tungsten	Backfill + Building materialization dual-wheel drive	Resource recovery rate increased by 10%+, tailings comprehensive utilization rate over 60%, cumulatively reduced tailings pond inflow by approx. 3.7 million tons

Shuikoushan Nonferrous	Intelligent sorting pre-discarding + dry tailings sand external sales + paste backfill + wastewater recycling	Waste rock 95,000 t/yr all building materialized, dry tailings sand 200,000 t/yr external sales, tailings pond zero discharge
Tongling Nonferrous	New low-carbon cementitious material replacing cement	Dosage 60%–70% of cement, backfill cost reduction 1/3, three-year tailings consumption 10 million tons
Hunan Nonferrous	Waste residue internal direct supply channel + hazardous waste sharing center	Solid waste recycling rate from less than 30% to 90%, annual benefit over 100 million yuan
Lomon Panzhihua	External magnetic separator pre-concentration + high-efficiency titanium separation collector	Iron recovery rate 5.96 percentage points above planning target, titanium resource comprehensive utilization rate increased to 45%

These cases collectively prove that the technology combination of physical-field separation + solid waste-based cementitious material has been verified in different mineral types, different regions and different ownership enterprises, and has the engineering conditions for large-scale replication.

(IV) Standards and Policy Support

Category	Main Content
National Strategy	Comprehensive solid waste treatment action (deployed by State Council Executive Meeting in December 2025)
Quantitative Targets	2025 bulk solid waste comprehensive utilization rate 57%; 2030 resource utilization rate over 60%
Tax Incentives	Tailings resource tax exemption/reduction; backfill replacement coal reduction 50%;

	comprehensively utilized solid waste temporarily exempt from environmental protection tax; product revenue included at 90% for taxable income
Green Mine	Construction incorporated into government performance assessment; many regions require 95% of large and medium mines to build province-level+ green mines by end of 15th Five-Year Plan
Zero-Waste Construction	113 cities implementing 3000+ zero-waste city construction projects; zero-waste group pilots continuing
Industry Standards	"Solid Waste-Based Cementitious Material for Road", "Technical Specification for Application of Copper Tailings as Road Material", "Technical Standard for Comprehensive Utilization of Tailings Micro Powder", etc. have been established in many regions

IX. Conclusions and Promotion Recommendations

Combining technical principles, engineering data and industrial conditions, four conclusions and six promotion recommendations can be given. These contents are not only a conclusion to the analysis results of this report, but also can be directly used as a basis for project initiation and business communication.

(I) Main Conclusions

Conclusion 1: The coupling system is technically viable and logically rigorous.

Physical-field mineral processing technology solves separable, cleanable and economical, while geopolymers cementitious material solves usable, stable and durable. The former physically disassembles mixed materials into valuable concentrate, construction-materializable aggregate, active alumino-silicate fine material and heavy metal enriched phase; the latter provides large-scale, high-

value and stable outlets for the latter three types of materials, and permanently locks heavy metals in a three-dimensional network of quasi-geological minerals. The interface between them is the material flow itself, requiring no additional adaptation.

Conclusion 2: Economic viability has already crossed the break-even point.

On the backfilling side, low-carbon cementitious material replacing cement can reduce backfilling cost by about one-third, saving over 50% of cementitious material; on the processing side, source pre-concentration waste discarding can reduce 30%-50% of ineffective processing volume, with subsequent whole-process energy, water and steel consumption reduced by approximately 40%; on the policy side, resource tax reduction, environmental protection tax exemption, and income tax reduction form superposed dividends. The mine tailings pond is no longer just a cost center, but is becoming a profit source.

Conclusion 3: Environmental and safety risks are fundamentally resolved.

Shifting from end-of-pipe stockpiling to source reduction means that the incremental growth of tailings ponds is fundamentally curbed. Existing cases have achieved consecutive months of tailings pond zero discharge, 100% wastewater recycling, 95% reduction in heavy metal leaching, internal digestion of hazardous waste, and solid waste recycling rate increased from less than 30% to 90%. Zero-waste mining, processing and metallurgy is not a visionary statement, but an engineering state that has been verified.

Conclusion 4: Industrial conditions are mature, with a foundation for large-scale replication.

The technology supply side has formed a complete system from equipment, materials to process packages; industrialization carriers have laid out projects in 27 provinces and regions nationwide; there are already successful cases covering ferrous, non-ferrous, gold, phosphorus chemical and other fields in the industry

for benchmarking; standards and policy supporting measures continue to improve. This is a promotion window period where everything is ready.

(II) Promotion Recommendations

Recommendation 1: Advance in a one mine one policy manner, without rigidly applying a general scheme.

The chemical composition, particle size distribution and activity of solid waste from different mineral types vary greatly. Tongling Nonferrous's approach is worth learning from: establish a tailings sand database for different mines, quickly search for suitable cementitious materials and utilization schemes based on the database, achieving one mine one policy. It is recommended to conduct systematic material characterization (chemical composition, mineral composition, particle size distribution, activity evaluation) in the early stage of the project, and customize physical-field sorting processes and cementitious material formulations accordingly.

Recommendation 2: Prioritize implementation in mining areas with high pollution risk + high transportation cost.

There are three judgment criteria: first, tailings contain environmental risk components such as heavy metals, with high stockpiling cost and major hidden dangers; second, there is strong demand for building materials market around the mining area or large underground backfill demand; third, short transportation radius and strong local consumption capacity. Mining areas meeting these three criteria have the shortest investment payback period and strongest demonstration effect.

Recommendation 3: Make source sorting the first priority of investment.

When funds are limited, priority should be given to investing in physical-field pre-concentration waste discarding system, which has small investment, quick effect,

short payback period, and can immediately produce reduction benefits. After the pre-concentration system operates stably and material properties are clearly understood, then advance the construction of geopolymer cementitious material production lines to form a complete closed loop.

Recommendation 4: Proactively connect with policy tools, and include policy dividends in the project model.

Policy tools such as resource tax reduction, environmental protection tax exemption, income tax reduction, green mine evaluation bonus points, and green credit support should be fully included in economic calculations. Practice in some regions shows that resource tax reduction alone can reduce corporate tax burden by an order of magnitude. It is recommended to connect with local tax, natural resources, and ecological environment departments at the project initiation stage to clarify applicable conditions and application paths.

Recommendation 5: Establish a classified and graded product system to avoid low-price disorderly competition.

Materials output by physical-field sorting should be directionally matched to downstream by grade: high-grade materials flow to fine chemicals and high-value materials; medium-grade materials flow to traditional building materials; low-grade materials flow to backfilling and road base materials. The quality-differentiated sorting and optimal material optimal use practices of Tongling Nonferrous and Shukongping Phosphate Mine prove that graded utilization is the core path to maximizing resource value.

Recommendation 6: Promote standard development and seize industry discourse power.

It is recommended to jointly promote group standards and local standard project initiation in directions such as performance indicators, testing methods, construction specifications, and environmental risk assessment of solid waste-

based cementitious materials, together with industry associations and research institutes, transforming mature project experience into replicable technical rules.

(III) Conclusion

Mining, processing and metallurgy are basic industries for human beings to obtain material wealth, and also the industries with the largest solid waste generation. For a long time, solid waste governance in these three stages has relied on the linear model of stockpiling — closure — reclamation, essentially transferring problems from the present generation to the future, and from enterprises to society.

The coupled application of physical-field mineral processing technology and geopolymer cementitious material provides a different possibility: making every ton of ore destined not to become garbage the moment it leaves underground. Separation is completed at the source, cementation is closed-loop at the end, pollutants are locked in the lattice, and carbon emissions are omitted at room temperature. This is not a patch on the traditional mining-processing-metallurgy flowsheet, but a reorganization of it.

When tailings ponds no longer grow, when waste rock becomes building materials, when smelting slag returns to backfill bodies, when solid waste comprehensive utilization rate increases from less than 30% to 90%, what zero-waste mining, processing and metallurgy depicts is actually an industrial form with higher resource efficiency. This road has already been walked by some, and there are already replicable blueprints.

References

1. Li Siyou, Li Lixia, Zhang Hongliang, et al. Research progress on tungsten ore pre-concentration waste discarding technology [J]. Conservation and Utilization of Mineral Resources, 2023, 43(3): 89-95.

2. Zhang Li, Wang Changfu. Research progress on vanadium-titanium magnetite resource processing technology and comprehensive utilization [J]. Conservation and Utilization of Mineral Resources, 2023.
3. Physical Mineral Processing (Encyclopedia Entry). Sorting Principles, Method Classification and Application Fields.
4. JXSC Mining. Waste to Wealth: Smart Tech Boosts Iron Ore Profits by \$100M.
5. JXSCTeam. Pre-Concentration: Cutting Costs by Rejecting Waste Early.
6. State-owned Assets Supervision and Administration Commission of the State Council. China Minmetals promotes high-quality development of metallurgical mining industry through resource conservation and recycling.
7. Hunan Provincial Department of Industry and Information Technology. Shuikoushan Nonferrous Metals Solid Waste Comprehensive Treatment Selected as Provincial Positive Typical Case, 2026-04-15.
8. Hengyang Municipal People's Government. Zero-Waste City | Technology Empowers Solid Waste Governance, Industry Synergy Green Transformation, 2026-04-13.
9. China Economic Net. Gansu Jinchang Turning Waste into Gold for Deep Recycling, 2025-12-24.
10. China Mining News. From Selective Mining to Full Utilization (Green Mining Special Report), 2026-09-08.
11. Deng Funan, Solid Waste Professional Committee of China Environmental Protection Industry Association, Solid Waste Comprehensive Utilization Professional Committee of China Bulk Cement Promotion and Development Association. Exploration on Collaborative Resource Utilization of Solid Waste to Solve Environmental and Resource Problems, 2025.
12. Study on preparation of geopolymers from low-silicon iron tailings [J]. China Mining Magazine.
13. Research progress on resource utilization of phosphogypsum, phosphorous tailings and yellow phosphorus slag through geopolymerization reaction. Solid Waste Research Center.
14. Research progress on tailings solidification using alkali-activated geopolymerization reaction [J]. Conservation and Utilization of Mineral Resources.
15. Research progress on preparation of cementitious materials from non-ferrous metallurgical slag [J]. Gold Science and Technology, 2020, 28(5): 621.
16. Solid Waste-Based Geopolymer Cementitious Materials: Theory, Application and Development. Engineering Technology Center for Resource Utilization of Industrial By-product Gypsum.

17. Palma G, Bolaños H, Huamani R, et al. Optimization of Geopolymers for Sustainable Management of Mine Tailings[J]. *Minerals*, 2024, 14(10).
18. Stabilization and solidification of iron ore tailings using alkali-activated geopolymer[J]. *Scientific Reports*.
19. Geopolymer Technologies for Mine Tailings Valorization. Nature Index Topic Summary.
20. Study on Preparation and Solidification Mechanism of Copper, Manganese Slag/Fly Ash Geopolymer (Dissertation).
21. The Utilization of Alkali-Activated Lead–Zinc Smelting Slag for Chromite Ore Processing Residue Solidification/Stabilization[J]. *IJERPH*, 2021, 18(19): 9960.
22. Study on low-carbon solid waste cemented gold tailings mine backfilling [J]. *Mining Technology*.
23. Li S, Guo Z, Ma Y, et al. Preparation and Optimization of Backfill Slurry from Ultrafine Tailings in Tianxing Iron Mine[J]. *Processes*, 2026, 14(4).
24. Application progress of external field enhancement technology in high-purity quartz sand preparation [J]. *Metal Mine*, 2026, 55(5): 237.
25. Research progress on green resource utilization of heavy metal-containing tailings. National-Local Joint Engineering Research Center for Metallurgical Waste Gas Resource Utilization.
26. Ultrasonic Enhancement for Mineral Flotation: Technology, Device, and Engineering Applications[J]. *Minerals*, 2024, 14(10): 986.
27. Tongling Municipal People's Government. [Zero-Waste City Construction] Treating Waste with Waste Lets Mines Turn Green and Reborn.
28. Tongling Nonferrous Metals Group Digital News. Exploring a New Path of Turning Tailings Sand into Treasure, 2025-01-07.
29. Chizhou Municipal Bureau of Natural Resources and Planning. Reply to Recommendation No. 20 of the 5th Session of the 5th Municipal People's Congress.
30. Shaanxi Provincial Department of Natural Resources, etc. Notice on Continuously Promoting Green Mine Construction, 2025-01-10.
31. Chongqing Municipal People's Government Website. Resource Tax Law Implemented for Six Years, Chongqing Enterprises Cumulatively Reduced/Exempted Resource Tax by 880 Million Yuan, 2026-09-02.
32. Huzhu Green Building (Beijing) Technology Co., Ltd. Gathered-Magnet Permanent-Magnet High-Intensity Magnetic Quality Improvement Technology for Lignite and Its Application, 2025.

33. Resource Tax Law of the People's Republic of China and Relevant Local Implementation Rules.