OPEN ACCESS INTERNATIONAL JOURNAL OF SCIENCE & ENGINEERING

Potential Use of Jarosite Waste as an Eco-Friendly Construction Material

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Abstract: The industrial processing of zinc generates large quantities of jarosite, a hazardous by-product classified as toxic due to its heavy metal content and acidic nature. Improper disposal of jarosite poses significant environmental and health risks. This study investigates the potential of utilizing jarosite waste as a sustainable construction material in civil engineering applications. Laboratory experiments were conducted to evaluate the physical, chemical, and mechanical properties of jarosite when blended with other construction materials such as cement, sand, and fly ash. Results indicate that, with proper treatment and proportioning, jarosite can partially replace conventional materials in concrete and bricks without compromising structural integrity. The study highlights the environmental and economic benefits of reusing jarosite, promoting a circular economy approach in the construction industry. However, further large-scale field validations are necessary to assess its long-term performance under real
Keywords: Jarosite waste, Hazardous material, Sustainable construction, Waste utilization, Civil engineering materials, Industrial by-product, Circular economy, Eco-friendly concrete, Waste valorization, Environmental management

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I. INTRODUCTION

Rapid industrialization and the growing demand for non-ferrous metals, especially zinc, have led to a significant increase in industrial waste generation. Among these wastes, jarosite is a major by-product produced during the hydrometallurgical extraction of zinc through the roasting-leaching-electrowinning (RLE) process. Jarosite is categorized as a hazardous waste due to its acidic nature and the presence of toxic heavy metals such as lead, cadmium, and arsenic. Improper disposal of jarosite in landfills not only consumes valuable land resources but also leads to serious environmental pollution, including leaching into groundwater and degradation of soil quality. The management and safe disposal of jarosite present a critical challenge for zinc-producing industries worldwide. In this context, the concept of waste valorization—transforming waste into useful materials—has emerged as a sustainable and economically viable solution. Civil engineering, particularly the construction sector, offers vast potential for the reuse of industrial wastes, including fly ash, slag, red mud, and now, jarosite.

The present study explores the utilization potential of jarosite waste as a construction material in civil engineering applications. It focuses on incorporating jarosite into cement-based products such as concrete and bricks by partially replacing traditional ingredients like cement or fine aggregates. The research aims to assess the mechanical, physical, and environmental performance of the resulting materials and determine their feasibility for large-scale applications. Utilizing jarosite in construction not only supports waste minimization and resource conservation but also aligns with global efforts toward achieving a circular economy and sustainable infrastructure development. However, scientific validation is essential to ensure that the use of jarosite does not compromise structural integrity or pose environmental hazards. This paper presents experimental findings, discussions, and conclusions regarding the practical use of jarosite in construction, contributing to the broader goal of sustainable waste management in civil engineering.

Page Size and Layout

II.MATERIALS AND COMPOSITION

The materials used in this study were selected based on their availability, compatibility with jarosite, and relevance to conventional civil engineering practices. The primary focus was on evaluating jarosite as a partial replacement material in cementitious and construction applications. The details of the materials and their respective properties are described below.

2.1 Jarosite Waste

Jarosite was collected from a zinc processing plant where it is produced as a residue from the hydrometallurgical leaching process. The waste appeared as a fine, reddish-brown powder with low plasticity and poor binding properties. Its chemical composition, determined through X-ray fluorescence (XRF) analysis, revealed the presence of iron, sulfate, zinc, lead, and trace amounts of cadmium and arsenic. Major oxides found include Fe_2O_3, SO_3, ZnO, and SiO_2.

Table 1: *Typical Chemical Composition of Jarosite Waste (by % weight)*

Component	Fe_2O_3	SO_3	ZnO	SiO_2	PbO	CaO	Al_2O_3	Cd	As
%	30–40	20–30	5–10	5–8	<1	<5	<5	Trace	Trace

The material was oven-dried, sieved, and stored in sealed containers to prevent moisture absorption and contamination prior to testing.

2.2 Cement

Ordinary Portland Cement (OPC) of 43 grade conforming to IS 8112:2013 was used as the primary binder. The cement was tested for standard consistency, initial and final setting time, and compressive strength.

2.3 Fine Aggregate

Locally available river sand conforming to Zone II of IS 383:2016 was used as the fine aggregate. The sand was clean, well-graded, and free from organic impurities.

2.4 Coarse Aggregate

Crushed granite stones of 10 mm and 20 mm nominal sizes were used. The aggregates complied with IS 2386 and were tested for specific gravity, water absorption, and crushing value.

2.5 Additional Binders and Additives (if used)

In some mixes, industrial by-products such as **fly ash** and **lime** were added to improve workability and reduce the leachability of heavy metals from the jarosite. Superplasticizers complying with IS 9103 were used to enhance the workability of the concrete mixtures without increasing water content.

- Column Width 86.8 mm (3.42")
- Column Height – 271.4 mm (10.69")
- Space/Gap between Columns - 5.0 mm (0.2").

III.TESTING METHODOLOGY

To evaluate the suitability of jarosite waste as a construction material, a series of laboratory tests were conducted. These tests aimed to assess the **physical, mechanical, and environmental performance** of jarosite-based construction materials, primarily concrete and brick specimens.

3.1 Mix Design and Sample Preparation

Concrete mixes were prepared by partially replacing cement or fine aggregates with jarosite waste in various proportions (e.g., 0%, 5%, 10%, 15%, and 20% by weight). Control mixes without jarosite were also prepared for comparison. Standard procedures as per IS 10262:2019 were followed for mix design. The water–cement ratio and admixture dosage were kept constant to isolate the effect of jarosite.

For each mix, cube specimens (150 mm × 150 mm × 150 mm) and cylindrical specimens (150 mm diameter × 300 mm height) were cast and cured in water for 7, 14, and 28 days.

3.2 Physical Tests

- **Specific Gravity and Fineness**: Jarosite was tested for specific gravity using a pycnometer and fineness by sieve analysis and Blaine's air permeability method.
- **Consistency and Setting Time of Cement Paste**: Tests were conducted as per IS 4031 (Part 4 & 5) to observe the effect of jarosite on cement hydration.
- **Workability (Slump Test):** The workability of concrete mixes was measured using the slump cone test (IS 1199:2018).

3.3 Mechanical Strength Tests

- **Compressive Strength:** Tested on concrete cubes after 7, 14, and 28 days of curing as per IS 516:1959.
- **Split Tensile Strength**: Performed on cylindrical specimens according to IS 5816:1999.
- **Flexural Strength (optional)**: Beam specimens were tested using two-point loading to determine the modulus of rupture, per IS 516.

3.4 Durability Tests

- **Water Absorption and Porosity**: Measured using the oven-dry and saturated weight method.
- **Acid Resistance Test**: Specimens were immersed in a 5% sulfuric acid solution to assess chemical durability.
- **Leaching Test:** Toxicity Characteristic Leaching Procedure (TCLP) or similar method was used to evaluate the release of heavy metals from jarosite-containing mixes.

3.5 Environmental Testing

pH and Electrical Conductivity: Jarosite was tested for its pH and EC to understand its interaction with cementitious systems.

Heavy Metal Analysis: The leachate from cured samples was analyzed using Atomic Absorption Spectroscopy (AAS) to detect elements like Pb, Cd, Zn, and As.

3.6 Detailed Description of Testing Methodology Adopted

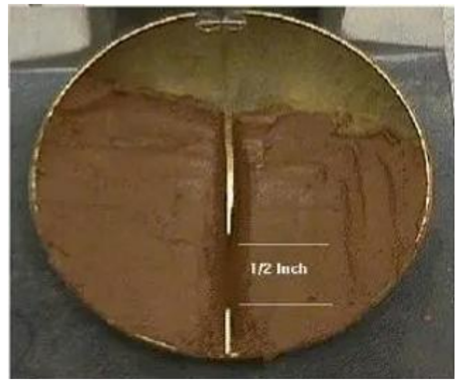
The list of tests performed and respective standards adopted as well as illustrate the flow diagram of the various studies undertaken. All the tests were conducted in laboratory as per the testing methods described in the relevant ASTM Standards. However, in the absence of ASTM Standards for a particular test, Indian Standards were followed. In addition, the leachate study is conducted in accordance with Toxicity Leachate Procedure (TCLP), United States Environment Protection Agency (USEPA) Method 1311

Table 2 Standards Adopted for Testing

Tests conducted	Standard adopted	
	ASTM Standard	Indian Standard
Particle size distribution (Sieve analysis)	ASTM D6913-04 [54]	BIS 2720 Part 4 [65]
Particle size distribution (Hydrometer	ASTM D422-63 [55]	BIS 2720 Part 4 [65]
Consistency limits	ASTM D4318-10 [56]	BIS 2720 Part 5 [66]
Soil classification system	ASTM D2487-11 [57]	BIS 1498 Part 2.2 [67]
Specific gravity	ASTM D854-10 [58]	BIS 2720 Part 3 [68]
Differential free swell index	-	BIS 2911 Part 3 [59]
Unconfined Compressive Strength	ASTM D2166-13 [62]	BIS 2720 Part 10 [70]
Split Tensile Strength	ASTM D3967 [63]	BIS: 10082 [71]

3.7 Consistency limits

The guidelines mention in relevant standards (mentioned in Table 3.4) were used for the determination of the consistency limits namely liquid limit and plastic limit.



3.8 Freezing–Thawing Durability Test for Jarosite-Based Bricks

The freezing–thawing durability test for jarosite-blended bricks is performed to assess deterioration due to extreme environmental cycles and reacting jarosite with moisture, salt, and frost. Brick specimens produced using jarosite as a partial replacement (ordinarily standard size as per IS 1077 (190 mm × 90 mm × 90 mm) or molded size) are first cured under controlled conditions for 28 days. Each of the brick specimens were then saturated in clean water for 24 hours. The saturated brick specimens were then placed into a freezing chamber kept at –18 °C for 4 hours, followed by immediate thawing in water at a minimum of +4 °C to +10 °C for another 4 hours. This resulted in a complete freeze–thaw cycle. These operations are repeated for either 25 to 50 freeze–thaw cycles to accelerate environmental weathering from freezing and thawing in the lab.

After the completion of the freeze–thaw cycles, our bricks (five bricks from each batch) were dried down from their saturated weight to a constant mass, and inspected for visible distress (e.g. cracking, surface erosion, and edge breakage). We then calculate the weight loss percentage based on the following formula:

$$\% \text{ Weight Loss} = [(W_{initial} - W_{final}) / W_{initial}] \times 100$$

Where, $W_{initial}$ is the weight of the brick before the freezing–thawing test, and W_{final} is the weight of the brick after the completion of freeze-thaw cycles. We also measured the residual compressive strength of the brick and calculated the percentage strength loss based on the following formula:

$$\% \text{ Strength Loss} = [(F_{initial} - F_{final}) / F_{initial}] \times 100$$

Sample Proportion

Mixtures	Proportions
Jarosite	Untreated
	J+2.5% L
Jarosite-Lime	J+5.0% L
	J+7.5% L
	J+10% L
Jarosite-GGBS	J+10% G
	J+10% G+2.5% L
Jarosite-GGBS-Lime	J+10% G+5.0% L
	J+10% G+7.5% L
	J+10% G+10% L
Jarosite-GGBS	J+20% G
	J+20% G+2.5% L
Jarosite-GGBS-Lime	J+20% G+5.0% L
	J+20% G+7.5% L
	J+20% G+10% L
Jarosite-GGBS	J+30% G
	J+30% G+2.5% L
Jarosite-GGBS-Lime	J+30% G+5.0% L
	J+30% G+7.5% L
	J+30% G+10% L

IV.RESULT AND DISCUSSION

4.1 General

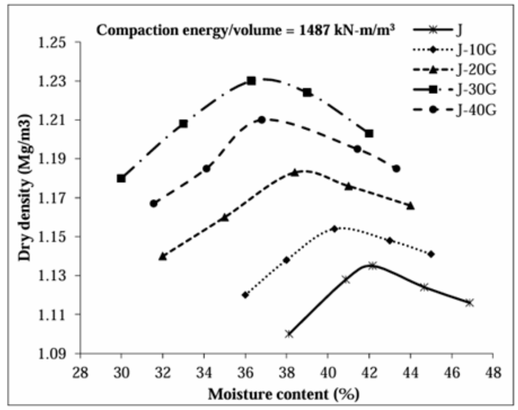
This section presents and discusses the experimental results obtained from the laboratory investigations on the utilization of jarosite waste as a potential construction material. The focus was on evaluating the physical, mechanical, and environmental performance of jarosite-based blends through compaction, strength, durability, and leachate studies. Jarosite was stabilized using Ground Granulated Blast Furnace Slag (GGBS) and hydrated lime to enhance its engineering properties.

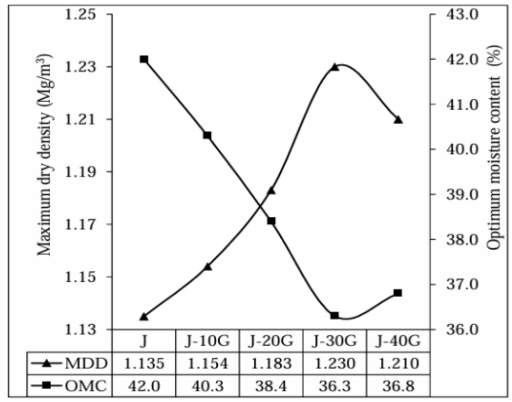
The study also explored the development of stabilized **jarosite bricks** and evaluated their suitability through **compressive strength**, **split tensile strength**, and **durability under freeze–thaw conditions**. Leaching behavior was analyzed using **TCLP–ICP** to assess environmental safety. The results indicate that with appropriate stabilization, jarosite can be effectively utilized in sustainable civil engineering applications.

4.2 Compaction Study

4.2.1 Effect of GGBS on Compaction Parameters

The compaction behavior of jarosite blended with GGBS (10%, 20%, 30%, and 40%) was studied using the mini compaction mould developed by Sridharan and Sivapullaiah. The untreated jarosite showed a **Maximum Dry Density (MDD)** of 1.135 Mg/m³ and an **Optimum Moisture Content (OMC)** of 42.09%. Upon blending with GGBS, the MDD increased while OMC decreased up to 30% GGBS addition. However, further addition (40%) resulted in a reverse trend, with a decrease in MDD and an increase in OMC (Figure 4.1).



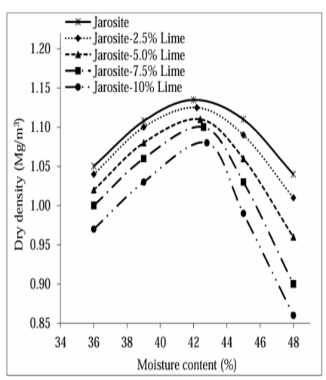


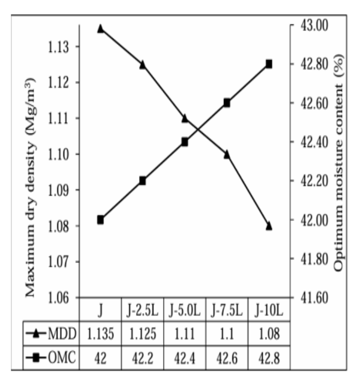
This behavior is attributed to the particle packing phenomenon, where GGBS particles fill the voids in jarosite, leading to denser packing and higher dry density up to an optimal point. Beyond this, excess GGBS causes segregation and weak bonding, reducing MDD.

4.2.2 Effect of Lime and GGBS on Compaction Parameters

The jarosite-GGBS mixtures were further modified with hydrated lime (2.5%, 5.0%, 7.5%, and 10%). The addition of lime led to an increase in OMC and a corresponding decrease in MDD across all mixes (Figures 4.2 to 4.4). This is due to the lower specific gravity of lime and its high reactivity, which promotes pozzolanic activity and agglomeration of particles, requiring more moisture for effective lubrication and compaction.

The combination of lime and GGBS significantly improved the compactness and stability of the blends, supporting their potential for geotechnical applications. A summary of compaction parameters for various jarosite-GGBS-lime combinations is presented in confirming the optimum performance at 30% GGBS and 2.5–7.5% lime content.





4.3 Strength Study

4.3.1 Unconfined Compressive Strength (UCS)

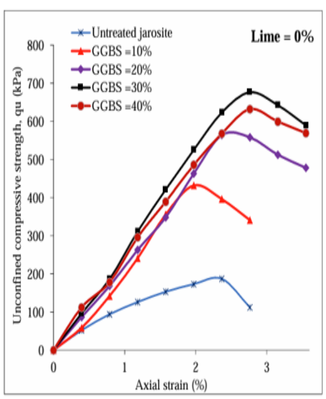
Samples were prepared using the compaction parameters (MDD and OMC) and tested as per ASTM D2166-06. The UCS increased significantly with the addition of GGBS and lime. The untreated jarosite exhibited low strength and poor structural integrity. The incorporation of 30% GGBS and 5–7.5% lime resulted in a **notable enhancement in compressive strength**, indicating improved pozzolanic bonding and matrix densification.

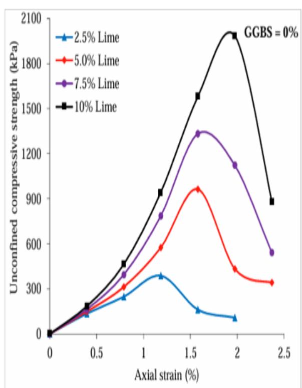
This improvement is due to the formation of calcium silicate hydrates (CSH) from the reaction between lime (source of calcium) and GGBS (source of silica and alumina). These hydration products fill voids and bind the particles together, improving strength characteristics.

4.3.2 Split Tensile Strength

Split tensile strength tests were conducted as per ASTM D3967. Similar to the UCS results, tensile strength also improved with increasing GGBS and lime content. However, the rate of improvement was relatively lower compared to compressive strength, as tensile properties are more sensitive to microcracks and pore distribution.

The best-performing mix (30% GGBS + 5% lime) achieved satisfactory tensile strength, indicating suitability for non-structural and load-bearing applications such as paver blocks or bricks.





4.4 Practical Implication – Brick Development

Bricks were cast using stabilized jarosite blends and tested for compressive strength, freeze–thaw durability, and leaching characteristics. The following observations were made:

Compressive Strength: Jarosite-based bricks met the minimum strength requirement for non-load-bearing applications, with maximum strength observed at 30% GGBS and 5% lime.

Durability (Freeze–Thaw Test): Repeated cycles of freezing and thawing revealed marginal weight and strength loss, indicating resistance to environmental degradation.

Leachate Analysis (TCLP–ICP): The leaching of heavy metals such as Pb, Zn, and Cd was well within permissible limits, confirming environmental safety when stabilized properly.

4.6 Development of Solidified, Durable, and Immobilized Unfired Bricks

As part of this study, unfired stabilized bricks were developed using jarosite waste blended with Ground Granulated Blast Furnace Slag (GGBS) and hydrated lime. The process followed the methodology described in **IS: 12894:2002** for manufacturing non-fired fly ash-based building bricks. These bricks were fabricated at the **Council of Scientific and Industrial Research – Advanced Materials and Processes Research Institute (CSIR–AMPRI), Bhopal, India** during a two-month project phase.

The bricks underwent **compressive strength testing after 7, 14, and 28 days of curing**, as well as **24-hour water absorption testing**. The results showed that the stabilized bricks consistently exceeded the minimum compressive strength requirement of **3.5 MPa** and maintained **water absorption below 20%**, meeting the standard criteria for unfired bricks as per Indian Standards.

Although the detailed process parameters and test data have not been disclosed due to an ongoing **patent application**, this innovation marks a significant step toward environmentally safe, cost-effective, and resource-efficient alternatives to traditional fired clay bricks. The use of hazardous jarosite waste, stabilized with industrial by-products, presents a sustainable pathway for **waste valorization** in civil engineering applications.

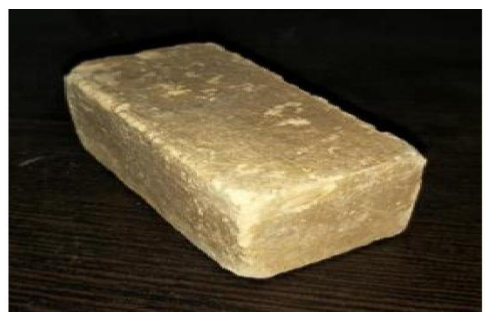


Figure: illustrates the stages of brick production and testing:

- (a) Stabilized jarosite bricks
- (b) Bricks before curing
- (c) Bricks after curing
- (d) Universal testing machine used for compressive strength test

4.6.1 Economic Viability

In India, jarosite waste is typically managed by producing **Jarofix**, a mixture of jarosite with 2% lime and 10% cement, which is both costly and environmentally limiting. This study compares the cost-effectiveness of the proposed **jarosite + 30% GGBS + 10% lime** blend against the conventional Jarofix method.

The cost of producing **1.0 m³ of stabilized jarosite** with 30% GGBS and 10% lime is approximately ₹494.97. Considering a standard brick size of 19 cm × 9 cm × 9 cm (0.001539 m³), the cost to produce one stabilized jarosite brick is roughly **₹0.77** under ideal conditions. Even after factoring in **material transportation (e.g., 500 km hauling distance for GGBS)**, the cost per brick remains around **₹3.00**, which is significantly lower than the market rate for conventional **fired clay bricks (₹5–7 per brick)**.

This demonstrates the **economic feasibility** of utilizing treated jarosite bricks, especially for **non-load-bearing and infrastructure projects**, thereby making it an attractive alternative in large-scale civil engineering works.

4.6.2 Construction Sequence and QA/QC Procedure

To apply the treated jarosite material in **field applications** such as **embankments or subgrades**, the following construction sequence is proposed:

1. **Mix Design Selection**: Select appropriate proportions of jarosite, GGBS, and lime based on application requirements.
2. **Dry Mixing**: Spread materials on the prepared soil subgrade and dry mix uniformly using mechanical equipment.
3. **Water Addition**: Add water according to the **Optimum Moisture Content (OMC)** derived from laboratory tests.
4. **Wet Mixing**: Carry out wet mixing using a plow and dozer to ensure homogeneity.
5. **Compaction**: Compact the blended material using a **vibratory or static roller** to achieve the desired **Maximum Dry Density (MDD)**.
6. **Curing Period**: Allow the compacted layer to gain strength for a minimum of **28 days** before placing any additional load or structure.
7. **Quality Assurance / Quality Control (QA/QC)**:
   - Conduct periodic sampling using core cutters.
   - Perform strength and moisture content testing in the laboratory.
   - Ensure compliance with design and field parameters.

4.7 Summary of Results

Optimum mix: **Jarosite + 30% GGBS + 5–7.5% Lime**

Maximum Dry Density (MDD): **1.230 Mg/m³**

Optimum Moisture Content (OMC): **36.30%**

UCS and tensile strength showed increasing trends up to 30% GGBS.

Bricks developed with this mix showed **acceptable strength**, **durability**, and **low leachability**, making them a viable product for sustainable construction.

V.CONCLUSION AND FUTURE SCOPE

Conclusion

This study aimed to investigate the potential reuse of hazardous jarosite waste, a by-product of zinc production, in the development of sustainable construction materials. Through extensive laboratory investigations involving compaction, strength testing, durability evaluation, leaching behavior, and brick development, the following conclusions were drawn:

Compaction Behavior:

The blending of jarosite with Ground Granulated Blast Furnace Slag (GGBS) and hydrated lime significantly improved its compaction characteristics. Optimum results were observed with 30% GGBS and 5–7.5% lime, achieving a maximum dry density of 1.230 Mg/m³ and optimum moisture content of 36.30%.

Strength Improvement:

Unconfined Compressive Strength (UCS) and split tensile strength tests demonstrated considerable strength gains with increasing GGBS and lime content. The optimized mixture fulfilled structural criteria for non-load-bearing construction applications.

Brick Development:

Scaled unfired bricks produced using the stabilized jarosite blend met Indian Standards for compressive strength (>3.5 MPa) and water absorption (<20%), proving their suitability for practical applications. This innovation, currently under patent, highlights the technical feasibility and durability of jarosite bricks.

Durability and Environmental Safety:

Freeze–thaw resistance and TCLP–ICP leachate analysis confirmed that the stabilized products are durable and environmentally safe, with heavy metal leaching remaining within permissible limits.

Economic Viability:

The cost of a stabilized jarosite brick was estimated to be ₹0.77–₹3.00, significantly lower than conventional clay bricks (₹5–7), establishing a cost-effective solution for large-scale use in civil engineering projects.

Field Implementation Strategy:

A detailed construction procedure and QA/QC protocol was proposed for the deployment of treated jarosite materials in infrastructure applications such as subgrades and embankments, ensuring quality and long-term performance.

Future Scope

While the study establishes a promising foundation for the utilization of jarosite waste, several areas remain open for further research and development:

1. Field Trials and Pilot Projects:

Full-scale field implementation under varying environmental conditions is essential to validate laboratory results and optimize long-term performance

2. Alternative Activators and Additives:

Exploration of other pozzolanic materials or alkali activators (e.g., fly ash, sodium silicate) may further enhance the mechanical and environmental performance of jarosite-based composites.

3. Life Cycle Assessment (LCA):

A comprehensive LCA can be conducted to quantify the environmental benefits of using jarosite over conventional disposal and material use methods.

4.Standardization&Guidelines:

Development of technical specifications and guidelines for the use of jarosite-based products in construction will aid regulatory acceptance and wider adoption.

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