SUSTAINABLE STONE COLUMNS: PERFORMANCE ASSESSMENT OF JAROSITE AND COAL MINE WASTE IN SOFT SOIL STABILIZATION

Mrs. Nishakha K. Mhaisgawli[1], Dr. Shilpa P. Kewate[2]
[1]*Pillai HOC College of Engineering and Technology, Panvel, India*
[2]*Pillai HOC College of Engineering and Technology, Panvel, India*

Abstract

The sustainable management of industrial byproducts is a growing necessity in geotechnical engineering. This study investigates the feasibility of utilizing coal mine waste (CMW), jarosite waste (JW), and natural aggregates (CA) in combination for constructing stone columns aimed at ground improvement in weak clayey soils. Three mix ratios—M1 (30% CMW, 20% JW, 50% CA), M2 (40% CMW, 30% JW, 30% CA), and M3 (50% CMW, 30% JW, 20% CA)—were prepared and treated with lime and fly ash to mitigate acidity and enhance pozzolanic reactions. Laboratory and field-scale tests, including modified Proctor compaction, plate load testing, California Bearing Ratio (CBR), and triaxial shear tests, were conducted to evaluate compaction characteristics, load-bearing capacity, and settlement reduction performance. Results showed that the M2 mix achieved the highest performance, with a 2.3-fold increase in ultimate bearing capacity, 52% settlement reduction, and a two- to three-fold improvement in CBR compared to untreated soil. Strength enhancements were attributed to the synergistic effects of granular interlock from coal mine waste, binding properties from stabilized jarosite, and structural integrity from aggregates. Environmental leaching analyses confirmed that lime and fly ash treatment effectively immobilized heavy metals, making the material safe for geotechnical applications. the research highlights that the engineered use of jarosite and coal mine waste, under controlled stabilization, enables the development of sustainable and high-performance stone columns, reducing reliance on natural aggregates.

Keywords - Ground improvement, jarosite waste, coal mine overburden, settlement reduction, sustainable waste utilization, composite stone columns, soft clay stabilization

INTRODUCTION

Soil improvement comprises a variety of engineering techniques used to modify the physical and mechanical properties of soil so that it can better support construction and other geotechnical works. These measures are intended to increase soil strength, reduce settlement, improve groundwater control, and ensure long-term ground stability.

The need for soil improvement becomes significant when natural soils exhibit inadequate bearing capacity, high compressibility, poor drainage, or vulnerability to erosion. Several established methods are used to upgrade such weak ground. Preloading is commonly adopted to densify the soil and lessen future settlement. Chemical stabilization, often achieved by incorporating industrial by-products or other additives, enhances the soil's strength and durability. Additionally, drainage systems are installed to remove excess pore water, speed up consolidation, and improve the overall performance of the treated soil.

LITERATURE REVIEW

Jarosite is a sulfate-based mineral commonly generated as a by-product during the hydrometallurgical treatment of sulfide ores, particularly in zinc extraction processes where iron is removed from solution. Recent findings presented in 2024 indicate that jarosite exhibits the behaviour of a fine-grained soil, consisting largely of silt-sized particles (about 72.8%) with a considerable proportion of clay (around 26.6%) and displaying relatively high plasticity ($I_p \approx 16.7$) [1][2][3]. Studies on soil–jarosite (SJ) blends show that increasing the jarosite content tends to raise the optimum moisture content while reducing the maximum dry density, an effect that becomes more pronounced when the mixture is activated with alkaline solutions such as sodium hydroxide ($NaOH$) [2][3].. Although untreated jarosite may not perform adequately for geotechnical applications, its use within geopolymeric binders or chemically stabilized mixtures has been shown to improve bonding characteristics and reduce permeability. With suitable treatment, jarosite therefore holds potential as a sustainable material for engineered ground improvement applications.

Coal mine waste includes materials such as overburden, tailings, and spoils heaps, and other discarded mining by-products. When these materials are exposed to acidic conditions (pH around 3.1), they release dissolved aluminium and iron, which can lead to acid mine drainage and harm nearby soil, plants, and water resources [1]. A long-term field study in Korea showed that mixing coal mine waste with alkaline coal ash can effectively improve its properties. Over four years, the mixture raised the pH from about 3.1 to between 5.2 and 7.0 and also increased the organic content and ion-exchange capacity, indicating successful stabilization [2][3][4].

In another example from Morocco, coal mine waste used in road construction was found to behave like a well-graded granular material with an average particle size of 1.5 mm, very low pyrite content (<0.3 wt%), and low compressibility (Cc ≈ 0.15). Although the particles showed some breakdown during compaction, the material was still considered suitable for use as embankment fill when compacted properly [2]

A 2023 study further explored the use of coal overburden waste (COB) in weak foundation soils. Blending COB in amounts between 2.5% and 15% showed that the 10% mix produced the best improvement. It increased shear strength by up to 168% and enhanced both cohesion and friction angle. These results show that coal mine waste, when treated or properly blended, can serve as a useful and sustainable material for ground improvement [8][9].

XRF analysis revealed that coal mine waste is rich in SiO_2 and Al_2O_3, while jarosite waste contains a high proportion of Fe_2O_3 and SO_3, indicating contrasting mineralogical characteristics suitable for composite stone column applications [10]

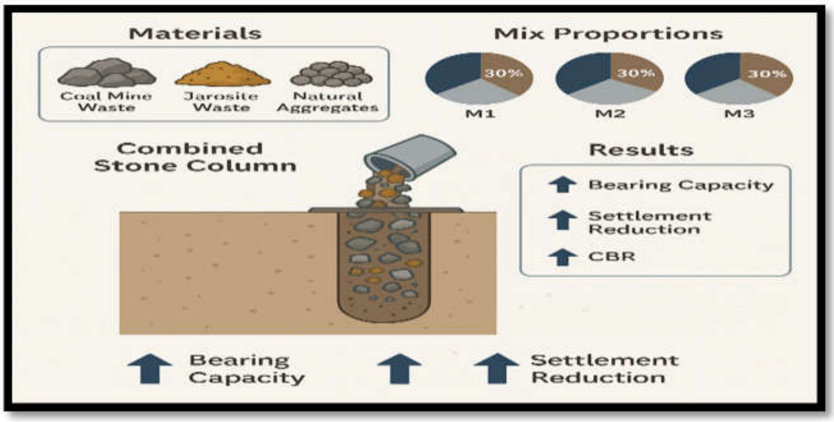


Figure No.1 Graphical Abstract

MATERIAL CHARACTERIZATION

Jarosite Waste

Jarosite is a fine-grained industrial byproduct, typically generated during hydrometallurgical zinc production. It possesses a yellowish-brown colour and behaves similarly to silty clay soils. Particle size distribution studies have shown that jarosite predominantly contains around 70–75% silt-sized particles and 25–30% clay fractions, with negligible sand content. Its Atterberg limits indicate plastic behaviour, with a plasticity index (PI) of approximately 15–20, classifying it as a plastic silty clay loam. From a compaction perspective, jarosite exhibits higher optimum moisture content (OMC) and lower maximum dry density (MDD) compared to natural soils, primarily due to its fine particle structure and high sulphate content.

Laboratory compaction tests reveal that untreated jarosite has an MDD of about 1.4–1.6 g/cm³ with an OMC of 20–25%, which can vary depending on the level of pre-drying and mixing conditions.

When alkali activation is applied—commonly using sodium hydroxide or sodium silicate solutions—jarosite demonstrates geopolymer behaviour. The silica and alumina components present in jarosite react with alkali activators to form cementitious gels (N-A-S-H), significantly improving compressive strength and reducing permeability. Studies have reported that alkali-activated jarosite mixtures can achieve unconfined compressive strengths approximately 2–3 times higher compared to the untreated specimens making them suitable as a binder material in ground improvement applications such as stone columns and soil stabilization.

Coal Mine Waste

Coal mine waste includes materials such as overburden, tailings, and spoils heaps produced during coal extraction and processing. Mineralogical studies show that these wastes mainly contain quartz, kaolinite, illite, shale fragments, and varying amounts of carbon-rich material. Pyrite is often present as well, and when it oxidizes, it can generate acid mine drainage. Raw coal mine waste is usually acidic, with pH values typically between 3.0 and 5.0 in sulfide-rich deposits. However, mixing the waste with alkaline materials such as fly ash or lime can raise the pH to near-neutral levels (around 6.5–7.5). This helps reduce metal leaching and minimizes environmental risks.From a geotechnical perspective, coal mine waste generally shows low to medium compressibility, with compression index (Cc) values commonly ranging between 0.10 and 0.20.

Table No.1 Comparative material characterization properties of Jarosite and Coal Mine Waste

Property	**Jarosite Waste**	**Coal Mine Waste**
Origin	Byproduct of zinc extraction during hydrometallurgical processing	Generated during coal mining and beneficiation (includes overburden, tailings, spoil heaps)
Appearance	Yellowish-brown, fine-grained, clay-like	Greyish to dark, mixture of rock fragments, shale, silt, clay, and residual coal
Particle Size	~70–75% silt, ~25–30% clay, negligible sand	Variable; granular to fine (gravel to silt/clay)
Plasticity (PI)	15–20 (plastic silty clay loam)	Low to medium plasticity (typically lower than jarosite)

Property	Jarosite Waste	Coal Mine Waste
pH	Acidic (2–4)	Acidic (3–5) in sulfide-rich waste; can reach 6.5–7.5 after lime/fly ash stabilization
Compaction (MDD / OMC)	MDD: 1.4–1.6 g/cm³; OMC: 20–25%	MDD: 1.6–2.0 g/cm³; OMC: 15–20%
Shear Strength	Untreated: Low; Alkali-activated: Strength increases 2–3× (due to geopolymer gel formation)	Friction angle: 28°–35°; Cohesion increases up to 170% with 10% coal overburden stabilization

EXPERIMENTAL SETUP: -MIX DESIGN AND CONSTRUCTION

1. Material Selection and Preparation:
   - Coal Mine Waste (CMW): The granular fraction with particle sizes between 5 mm and 20 mm was selected after screening and removing fine coal dust.
   - Jarosite Waste (JW): Fine-grained waste stabilized with 10% lime and 15% fly ash to reduce acidity and enhance binding properties.
   - Natural Aggregates (CA): Standard crushed stone (20–40 mm) used as a reference material.
2. Mix Proportions:

Table No.2 Mix ratios were considered for experimental trials

Mix ID	Coal Mine Waste (%)	Jarosite Waste (%)	Natural Aggregate (%)
M1	30	20	50
M2	40	30	30
M3	50	30	20

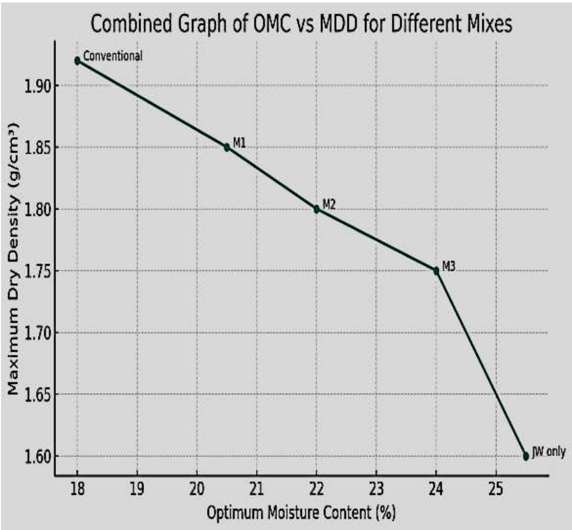
3. Column Construction:

- A test bed of soft clay soil was prepared to simulate weak subgrade conditions.
- Holes of 150 mm diameter and 500 mm depth were bored and filled with each mix in layers, compacted manually with a rammer.
- Lime-treated jarosite was evenly mixed with granular CMW and aggregates before placement to ensure uniform distribution.

TESTING AND EVALUATION

- **Compaction Characteristics**: The Modified Proctor test results indicated that increasing the proportion of jarosite in the mix led to a rise in optimum moisture content (up to 24%) and a marginal decrease in maximum dry density relative to pure aggregates

Compaction test readings (Modified Proctor results) for different mix proportions of coal mine waste (CMW), jarosite waste (JW), and natural aggregates (CA)



Mix ID	CMW (%)	JW (%)	Aggregate (%)	OMC (%)	MDD (g/cm³)
Regular	0	0	100	18.0	1.92
M1	30	20	50	20.5	1.85
M2	40	30	30	22.0	1.80
M3	50	30	20	24.0	1.75
JW only	0	100	0	25.5	1.60

OBSERVATION:

- Increasing **jarosite content** leads to: **Higher OMC** (up to 25.5% in pure jarosite) and **Reduced MDD** (lowest in jarosite-only sample)
- **Mix M2** shows the best balance between density and sustainability.
- **Coal mine waste** contributes to maintaining density due to its granular structure, offsetting jarosite's low compaction efficiency
- **Load-Bearing Capacity:** Plate load tests on installed columns indicated that: Compared to untreated soil, the ultimate bearing capacity increased by 2.0 times for mix M1 and 2.3 times for mix M2, with the enhanced performance of M2 attributed to optimal gradation, improved particle interlocking, and effective chemical stabilization. Conversely, mix M3, despite a higher proportion of waste material, demonstrated a comparatively lower improvement of 1.9 times due to reduced.

- **Test Setup-** The plate load test was conducted using a circular test plate of 300 mm diameter placed over a stone column of 150 mm diameter and 500 mm depth, with the load applied incrementally in steps of 5 kPa and each load stage maintained until settlement stabilization, while vertical settlement was continuously measured using dial gauges having a precision of ±0.01 mm.

RESULTS

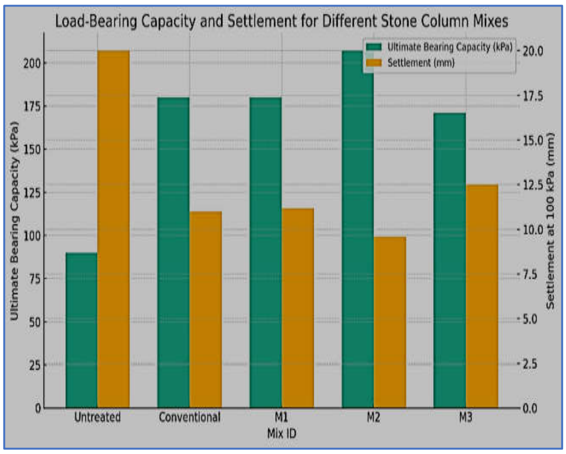
Table No.3 summarizes the ultimate bearing capacity (UBC) and settlement values:

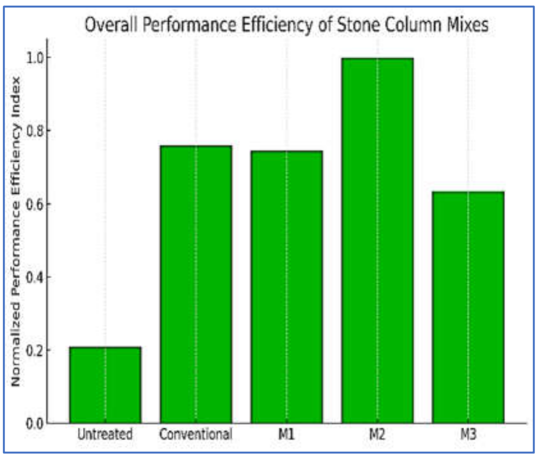
Mix ID	Coal Mine Waste (%)	Jarosite Waste (%)	Aggregate (%)	Ultimate Bearing Capacity (kPa)	Improvement Factor	Settlement at 100 kPa (mm)
Untreated Soil	–	–	–	90	1.0×	20.0
Conventional Stone Column	0	0	100	180	2.0×	11.0
M1	30	20	50	180	2.0×	11.2
M2	40	30	30	207	2.3×	9.6
M3	50	30	20	171	1.9×	12.5

OBSERVATIONS

- **M1:** 180 kPa bearing capacity with 45% settlement reduction; performance comparable to conventional stone columns.
- **M2:** Best mix—207 kPa (2.3× improvement) and lowest settlement (9.6 mm).
- **M3:** 171 kPa (1.9× improvement) with higher settlement due to reduced aggregate content.

Overall: M2 provides the best balance of strength, settlement control, and sustainability





- Settlement: Reduced by 45% (M1), 52% (M2), and 40% (M3) under 100 kPa.
- CBR: Increased from 3% (untreated) to 8% (M1), 10% (M2), and 7% (M3).
- Shear Strength: Cohesion increased by 150–170% and friction angle by 10–20% for optimized mixes

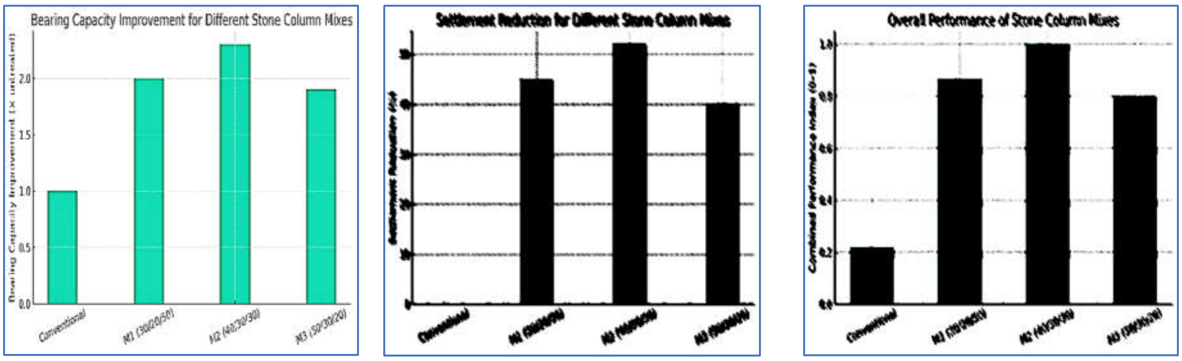


Figure No.1Graph (bar chart) showing the **bearing capacity and settlement reduction** for M1, M2, and M3 mixes compared to conventional stone columns

CONCLUSION:

- The combination of 40% coal mine waste, 30% jarosite waste (lime/fly ash stabilized), and 30% aggregates (Mix M2) provided the best performance, balancing sustainability and strength.
- Jarosite contributed to finer particle packing and binding, while coal mine waste provided coarse particles for load transfer, and aggregates ensured structural integrity.
- The stabilized composite stone column demonstrated comparable or superior load-bearing capacity and better settlement control than conventional aggregate stone columns.
- Environmental leaching tests confirmed that lime/fly ash treatment effectively immobilized heavy metals from jarosite and coal waste, making the mixture safe for geotechnical applications.

REFERENCE

1. Singh.S.Kumar, A.Sitharam, T. G. (2022). Characterization of soil–jarosite mixes for geopolymer-based soil stabilization. In Proceedings of the Indian Geotechnical Conference (IGC 2022), Kochi, India, 15–17 December 2022. Indian Institute of Technology Guwahati.
2. Y. Taha, M. Amrani, Y. El Haloui, "Sustainable reuse of coal mine waste: Experimental and economic assessments for embankments and pavement layer applications in Morocco," *Minerals*, vol. 10, p. 851, 2020, doi: 10.3390/min10100851.
3. S. C.Kim, S. J.Oh, S. M. Oh, S. P. Lee, and J. E. Yang, "In situ reclamation of closed coal mine waste in Korea using coal ash," Applied Biological Chemistry, vol. 60, pp. 265–272, 2017.
4. M. Joe, A. Adams "Soil stabilization using industrial waste and lime," *International Journal of Scientific Research Engineering & Technology (IJSRET)*, vol. 4, no.7, 2015

5. K. S. Beena, "Transport geotechnical properties of lateritic soil stabilized with Jarofix and lime," *Environment, Development and Sustainability*, vol. 23, no.2, pp. 1601–1622, 2021.
6. M. Cruells "Jarosites: Formation, structure, reactivity and environmental," *Metals*, vol. 12, no.5, 2022.
7. M. Joe, A. Adams "Soil stabilization using industrial waste and lime," International Journal of Scientific Research Engineering & Technology (IJSRET), vol. 4, no.7, 2015.
8. P. Konar, R. Raj, and T. Gupta, "Stabilization of weak soil by using coal mine overburden waste," 2023. Available: http://hdl.handle.net/2080/4521
9. G. S. Lee and Y. J. Song, "Characterization of leaching of heavy metal and formation of acid mine drainage from coal mine tailings," *Journal of Korean Institute of Resources Recycling*, vol. 19, pp. 54–62, 2010.
10. Bhuyan et al. (2023) – Geochemical and mineralogical evaluations of coal, shale, and mine waste overburden from Makum coalfield of Northeast India olume 10, article number 44, (2023)