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# ALKALINE-ACTIVATED STEEL SLAG–RICE HUSK ASH GEOPOLYMERS FOR GOLD MINE TAILINGS STABILIZATION AND SUSTAINABLE ROAD CONSTRUCTION: A CRITICAL REVIEW

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**Abstract**
The increasing generation of mine tailings, metallurgical slags and agricultural residues has created a combined environmental-management and resource-efficiency challenge for the construction sector. Gold mine tailings (GMT) are particularly difficult to reuse because their fine-grained nature, variable mineralogy, potentially toxic elements and susceptibility to contaminant release can limit direct application in pavement earthworks. At the same time, steel slag (SS) and rice husk ash (RHA) are locally available wastes with complementary chemical characteristics that can be exploited through alkaline activation. This review synthesizes the engineering and environmental evidence on SS–RHA-based alkali-activated/geopolymeric binders for stabilization of mine tailings, with emphasis on pavement applications. The review examines the characteristics and reactivity of GMT, SS and RHA; mechanisms of alkaline activation; effects of precursor proportion, particle size, activator chemistry, water content, curing and Si/Al-related ratios; and resulting changes in plasticity, compaction, California Bearing Ratio (CBR), unconfined compressive strength (UCS), hydraulic conductivity and contaminant leachability. Evidence indicates that steel slag can contribute calcium-rich reactive phases and particle interlocking, while RHA provides a highly siliceous source that participates in the formation of binding gels under alkaline conditions. Their combination can therefore provide both mechanical improvement and immobilization of potentially toxic elements. However, performance is strongly mixture- and source-dependent, and excessive RHA, excessive alkalinity, unsuitable activator ratios, inadequate curing and insufficient particle-size control can reduce performance or increase environmental risk. The review identifies the need for integrated multi-response optimization, standardized leaching assessment, field-scale validation, life-cycle assessment and economic analysis. A research framework is proposed for developing locally sourced SS–RHA geopolymeric binders for sustainable pavement construction in Nigeria and other regions where mining, steel production and rice processing generate significant waste streams.

***Keywords***
*Gold mine tailings; steel slag; rice husk ash; geopolymer; alkaline activation; soil stabilization; road subbase; leachability; sustainability*

## 1. INTRODUCTION

Mining, steel production and agricultural processing generate large quantities of residues that require safe management and, increasingly, beneficial reuse. Mine tailings are the finely divided residues produced after valuable minerals are separated from ore. Their storage occupies land and may create risks associated with acid mine drainage and release of potentially toxic elements. The mining residues as materials contain heavy metals susceptible to leaching and their incorporation into construction materials requires effective immobilization strategies [1]. The problem is particularly important for gold mine tailings because the environmental legacy of tailings storage may persist long after mine closure [2].

Conventional soil stabilization relies heavily on cement and lime. These binders are technically effective, but their manufacture is energy intensive and associated with greenhouse-gas emissions [5]. This has stimulated research into alternative binders based on industrial and agricultural wastes. Steel slag is considered a promising precursor for soil stabilization because of its relatively high specific gravity, angular and rough particle surfaces, and chemical composition. Its mineralogical composition commonly includes calcium-bearing compounds, together with iron-rich phases such as magnetite and hematite. The presence of calcium-bearing phases can provide calcium ions that contribute to the formation of cementitious reaction products during alkaline activation. In addition, the angular and rough texture of steel slag particles can improve particle interlocking and contribute to better mechanical performance of the stabilized soil. However, free CaO and other expansive phases mean that the material requires appropriate conditioning and stabilization before some applications [6].

Rice husk ash is another promising precursor from agricultural residue. Controlled combustion of rice husk can produce an ash with high silica content and pozzolanic activity. RHA alone may have limited cementing capacity in some soils, but its silica content makes it valuable when combined with a calcium-rich source and an alkaline activator [7, 8]. The combination of SS and RHA is attractive because the two wastes can supply complementary constituents for alkaline-activated binding.

Geopolymerization or alkaline activation involves dissolution of reactive silica- and alumina-bearing phases in an alkaline environment, followed by reorganization and condensation into a hardened binding structure. Depending on precursor chemistry, calcium-rich systems may develop C-(A)-S-H-type products alongside N-A-S-H or related aluminosilicate gels. The resulting matrix can improve particle bonding, densification and strength while reducing contaminant mobility by physical encapsulation and chemical binding [9, 10, 11].

This review develops a materials-to-performance framework for alkaline-activated SS–RHA stabilization of mine tailings. It is based primarily on the literature synthesized in the selected recent studies. The objective is to critically organize the existing evidence, identify controlling variables and highlight the research requirements for translating laboratory-scale geopolymeric stabilization into reliable pavement practice.

## 2. REVIEW APPROACH

A narrative and thematic review approach was adopted. The evidence was organized around six themes: environmental and engineering characteristics of mine tailings; steel slag as a calcium-rich industrial by-product; rice husk ash as a silica-rich agricultural residue; chemistry and process variables governing alkaline activation; engineering performance of stabilized soils and mine tailings; and environmental, durability and sustainability requirements for pavement application. Priority was given to peer-reviewed studies and technical standards, with emphasis on studies directly addressing mine tailings, steel slag, RHA, geopolymerization and road-material performance.

The synthesis follows amaterial–process–structure–performance logic. Materials chemistry and mineralogy determine precursor reactivity; processing variables control dissolution and gel formation; microstructure governs densification, strength and transport; and the final engineering and environmental properties determine suitability for road construction.

## 3. GOLD MINE TAILINGS: ENVIRONMENTAL AND GEOTECHNICAL CHALLENGES

### 3.1 Origin, composition and environmental risk

Gold mine tailings are generated after crushing, grinding and mineral processing. Their particle-size distribution, mineral phases and chemical composition vary with ore type, beneficiation route and processing conditions. Studies on gold mine tailings have shown that their mineral composition commonly includes quartz, aluminosilicate minerals and iron-bearing phases, although the proportions may vary depending on the geological setting and the mineral-processing method used [1, 2, 3]. Some gold and sulfide mine tailings may also contain residual sulfide minerals, such as pyrite, particularly where the processed ore is sulfide-rich [3]. When these sulfide minerals are exposed to oxygen and water, they can undergo oxidation and contribute to the formation of acidic drainage. This process can increase the mobility of certain metals and metalloids and may therefore pose risks to surrounding soil and water resources [3, 4]. In sulfide-bearing tailings, oxidation can generate acidic drainage and increase the mobility of metals [3, 4, 12].

The environmental problem is therefore twofold. First, large tailings volumes require storage and long-term management. Second, the material may contain contaminants that can migrate under changing pH and moisture conditions. A stabilization technology intended for beneficial reuse must consequently achieve more than strength gain: it should also reduce contaminant mobility and maintain that immobilization under service-related wetting and drying conditions.

### 3.2 Geotechnical Limitations

Untreated mine tailings may have unsuitable plasticity, gradation, compressibility, bearing capacity or strength for direct use in pavement layers. Even where a tailings material appears granular, its fine fraction can influence moisture sensitivity and compaction. For pavement use, stabilization must produce a material

with adequate density, bearing capacity and strength while maintaining acceptable permeability and durability.

### 3.3 Routes for Beneficial Reuse

Reported approaches include cemented paste backfill, bricks, concrete-related products, pavement aggregates, embankment materials and soil stabilization. Geopolymerization is attractive because it can transform waste-derived aluminosilicate resources into a binding matrix while potentially reducing reliance on Portland cement. Mine-tailings-based geopolymers have been reviewed [13] and [14], while experimental studies have demonstrated alkali-activated tailings and slag systems [15, 16, 17].

## 4. STEEL SLAG AS A STABILIZATION PRECURSOR

### 4.1 Chemical and Physical Characteristics

Steel slag is generated during steelmaking and contains calcium-, iron-, silicon- and magnesium-bearing phases. Its relatively high density and angular texture can improve packing and particle interlocking in soil mixtures. The literature reviewed reported that increasing steel slag content can increase maximum dry density and reduce optimum moisture content in some soils, while also improving CBR and UCS [18, 19, 6].
The chemical advantage of steel slag in an SS–RHA geopolymeric system is its calcium-rich character. Calcium can participate in the development of calcium-silicate- and calcium-aluminosilicate-bearing reaction products when reactive silica and alumina are available. This makes steel slag complementary to RHA, whose principal contribution is reactive silica.

### 4.2 Expansion and environmental considerations

The principal limitation of steel slag is the presence of free lime and other potentially expansive phases. Hydration can cause volume change if the slag is not adequately conditioned. Particle-size control, aging or conditioning and mixture proportioning are therefore important before field application. Environmental assessment should also consider trace metals in the slag and their potential release under the expected service environment.

### 4.3 Evidence from soil stabilization

Steel slag has been investigated in lateritic and expansive soils. The literature generally reports reductions in plasticity and improvements in density, CBR and compressive strength, although the optimum dosage is not universal. A study reported an optimum steel slag content based on strength criteria for lateritic soil [6], and another study associated improvements in density with the higher specific gravity of steel slag [19]. These findings support the use of steel slag as a structural component, but also demonstrate why source-specific optimization is required.

## 5. RICE HUSK ASH AS A SILICA-RICH PRECURSOR

### 5.1 Availability and chemical potential

Rice husk is an agricultural residue generated during rice milling. When appropriately burned, the resulting ash can contain a high proportion of silica, including an amorphous fraction that is reactive in alkaline and pozzolanic systems. Nigerian studies have reported the potential of RHA as a soil-stabilization and construction material [7, 20].

### 5.2 Effect on Soil Properties

RHA generally has a low specific gravity and porous particle structure. Consequently, increasing RHA can reduce MDD and increase water demand when it replaces denser soil particles. At suitable dosages, however, its silica can participate in pozzolanic or geopolymeric reactions and improve CBR and UCS. Alhassan and Mustapha [7] reported improvement in CBR and UCS when RHA was combined with cement, while Ayodele et al. [21] demonstrated the potential of RHA-based geopolymer treatment for residual tropical soils.

### 5.3 Why RHA Benefits from Hybridization

RHA is most effective when its silica supply is balanced by reactive calcium and alumina. Excess RHA can leave unreacted silica and porous fines in the matrix, reducing density or increasing water demand. Hybridization with steel slag provides a route to balance silica-rich and calcium-rich constituents. Recent research works on steel slag–RHA systems support the potential of this interaction for improving strength and stabilization mechanisms [22, 23].

## 6. SELECTED LITERATURES DIRECTLY RELEVANT TO THE REVIEW

This section focuses on studies that are closely related to the present research, particularly those involving gold mine tailings, steel slag, rice husk ash, alkaline activation, and soil stabilization. The reviewed studies provide useful information on the ability of these materials to improve properties such as strength, bearing capacity, plasticity, permeability, and durability as explained in Table 1. They also show how factors such as material composition, mixture proportions, alkaline activation, and curing conditions can influence

stabilization performance. Bringing these studies together helps to show what has already been achieved, where important gaps still exist, and how the present study contributes to the development of an alkaline-activated steel slag–rice husk ash system for stabilizing gold mine tailings for road construction.

Table 1. Selected literatures directly relevant to the review

| Study | Material/system | Main focus | Key implication | Verified DOI |
|---|---|---|---|---|
| Oluwasola et al., (2020) [18] | Lateritic soil + steel slag | Index, compaction, CBR, UCS | Steel slag can improve engineering properties; optimum content is source-dependent | — |
| Mashifana et al., (2021) [16] | Gold mine tailings + BOFS + NaOH/KOH | Geopolymer strength and leaching | BOFS supplied Ca and greatly increased UCS; leaching risk was reduced | 10.1155/2021/9984494 |
| He et al., (2022) [13] | Mine-tailings geopolymers | Comprehensive review | Performance depends on precursor chemistry, activator, curing, durability and leaching | 10.1016/j.ceramint.2022.05.345 |
| Pan et al., (2023) [24] | Gold mine tailings + waste binder | Mechanical/hydration behaviour | Waste-derived binders can improve tailings strength and develop binding products | 10.3390/ma16020634 |
| Gao et al., (2024) [25] | Steel slag–fly ash geopolymer | Base stabilization and water stability | Steel slag increased strength; water stability is a key pavement criterion | 10.1080/10298436.2024.2308168 |
| Ikotun et al., (2024) [26] | Geopolymer pavement materials | Review of pavement applications | Pavement use requires integrated performance and sustainability assessment | 10.3390/su16135417 |
| Levandoski et al., (2025) [27] | Iron ore tailings + alkali-activated RHA + eggshell lime | Strength, mineralogy, leaching | Alkali-activated RHA systems can combine strength development with contaminant control | 10.3390/min15060567 |

| | | | | |
|---|---|---|---|---|
| Cai et al., (2025) [22] | RHA + steel slag + iron tailing powder | Stabilized soil performance | Combination of waste materials is promising but requires optimization of dosage and engineering responses | 10.3390/ma18020346 |
| Blayi et al., (2025) [28] | RHA-based soil stabilization | Systematic review | RHA generally reduces PI and increases CBR/UCS, while often lowering MDD and increasing OMC | 10.1016/j.clwas.2025.100446 |
| Wijesingha & Eisazadeh (2026) [29] | RHA + lime + bottom ash + coir fibre | Comprehensive review of fine-grained soil stabilization | Recent evidence supports multi-waste stabilization but highlights the need for sustainability and performance integration | 10.4186/ej.2026.30.2.13 |

## 7. FUNDAMENTALS OF ALKALINE ACTIVATION AND GEOPOLYMERIZATION

### 7.1 Reaction Stages

Alkaline activation can be simplified into dissolution, transport/reorientation and polycondensation or gel development. Under high pH, reactive silica and alumina are dissolved from the precursor. The dissolved species then reorganize and condense into a binding structure. In calcium-rich systems, calcium participates in calcium-bearing gels, while sodium provides charge balancing in aluminosilicate networks. Exact products depend on precursor chemistry, amorphous content, calcium availability, activator composition, curing and water content [30, 10].

### 7.2 Activator Chemistry

Sodium hydroxide and sodium silicate are among the most widely used activators. NaOH promotes dissolution by providing high alkalinity, whereas sodium silicate supplies soluble silica and modifies gel chemistry and kinetics. The sodium silicate-to-NaOH ratio strongly influences workability, reaction rate, microstructure and strength. Studies summarized in the reviewed literatures showed that an optimum ratio exists for a given precursor, and excessive silicate can reduce strength by shifting the Si/Al balance or introducing excess soluble species [31, 32, 33].

### 7.3 Si/Al Ratio and Precursor Balance

The Si/Al ratio influences the structure and mechanical response of geopolymeric binders. Literatures reviewed indicate that strength commonly increases toward an optimum composition and declines when the system becomes excessively silica-rich [34, 11]. For SS–RHA–GMT mixtures, the optimum cannot be selected solely from a theoretical Si/Al ratio because silica and alumina are distributed across crystalline and amorphous phases with different dissolution rates.

### 7.4 Water and Curing

Water facilitates mixing and ion transport but excessive water can increase porosity after hardening. Lower water contents generally produce denser matrices when sufficient workability is retained [35]. Curing time and temperature influence dissolution and reaction kinetics. Heat curing can accelerate early geopolymerization, but ambient curing is attractive for pavement applications because it reduces energy requirements and simplifies field implementation.

## 8. MICROSTRUCTURAL AND CHEMICAL CHARACTERIZATION

X-ray fluorescence (XRF) is used to quantify major oxides and evaluate whether a precursor contains silica, alumina, calcium and iron required for alkaline activation.
X-ray diffraction (XRD) identifies crystalline phases and helps determine whether the reactive fraction is likely to be crystalline or amorphous. XRD should therefore be interpreted together with XRF and FTIR.
Fourier-transform infrared spectroscopy (FTIR) provides evidence of Si–O, Al–O, OH and carbonate-related functional groups and can track changes associated with alkaline activation. Shifts in the main Si–O–T band can indicate changes in the aluminosilicate environment after reaction. Scanning electron microscopy (SEM) reveals particle morphology, pore structure and matrix continuity, while energy-dispersive spectroscopy (EDS) provides local elemental composition. The combined techniques provide stronger evidence of reaction and matrix development than any one technique alone.

## 9. ENGINEERING PERFORMANCE OF SS–RHA-STABILIZED MINE TAILINGS

### 9.1 Plasticity and workability

Reduction in plasticity is a common stabilization objective. Calcium-bearing additives can promote cation exchange, flocculation and agglomeration, while geopolymeric products bind particles into larger units.

### 9.2 Compaction

MDD is controlled by particle density, gradation, packing and reaction products, while OMC is affected by surface area, porosity and water consumption during reaction. Steel slag generally tends to increase MDD because of its high specific gravity and angular particles. RHA tends to decrease MDD at high replacement levels because of its low specific gravity and porous structure.

### 9.3 California Bearing Ratio

CBR is a principal pavement performance indicator because it reflects resistance to penetration and provides a practical measure of bearing capacity. Steel slag and geopolymeric binders can improve CBR through particle interlocking, densification and cementitious bonding. Soils with high CBR values (ranges from 15 to 100) are used in road construction. Standard CBR requirements for subgrade and improved subgrade are 5–15%, for subbase is 15–30%, for base course is 30–80% and CBR > 80% for base course [36]. The reviewed evidence indicates that soaked CBR is particularly useful for judging performance under adverse moisture conditions; optimization should therefore not rely on unsoaked values alone.

### 9.4 Unconfined Compressive Strength

UCS is useful for evaluating development of a coherent stabilized matrix and the influence of curing.

### 9.5 Hydraulic Conductivity

Hydraulic conductivity is a critical environmental and pavement parameter. A very permeable matrix can facilitate contaminant transport, while an excessively impermeable layer may interfere with drainage design. Stabilization changes pore-size distribution through particle packing and reaction-product formation.

## 10. DURABILITY AND GEO-ENVIRONMENTAL PERFORMANCE

### 10.1 Leaching and contaminant immobilization

For mine-tailings stabilization, strength alone is insufficient. A successful binder should reduce the release of potentially toxic elements under water exposure. Geopolymeric matrices can immobilize contaminants by adsorption, chemical incorporation and physical encapsulation. It was demonstrated the relevance of leaching behaviour in mine-tailings-based geopolymers [9], while the need to control metal release and acid drainage in stabilized sulfide tailings was emphasized [12].

### 10.2 Durability under service conditions

Road materials experience repeated wetting, drying, loading and temperature changes. Durability assessment should therefore include wet–dry cycling, strength retention, dimensional stability and hydraulic performance. Steel slag expansion and geopolymer shrinkage must be considered alongside contaminant immobilization. Curing conditions, water content, activator chemistry and microstructure strongly influence long-term durability.

## 11. MULTI-RESPONSE OPTIMIZATION USING RESPONSE SURFACE METHODOLOGY

The interaction among GMT, SS, RHA and alkaline activators makes one-factor-at-a-time optimization inefficient. Response Surface Methodology (RSM) provides a statistical framework for modelling multiple responses and identifying an operating region. Design-Expert or similar software can be used to fit quadratic models, assess ANOVA significance and generate response surfaces and desirability functions. The validity of the model can be checked through the following:

(i) Report the fitted model type, model significance, F-value and p-value.

(ii) Report $R^2$, adjusted $R^2$ and predicted $R^2$ together rather than relying on $R^2$ alone.
(iii) Report adequate precision and diagnostic plots such as residuals versus predicted values.
(iv) Use response-surface and contour plots to interpret interactions among SS, RHA and activator variables.
(v) Validate the selected optimum with independent laboratory specimens and report prediction error.
(vi) Where predicted $R^2$ is undefined or unstable, investigate model structure, residual degrees of freedom and replication before making optimization claims.

## 12. SUSTAINABILITY AND CIRCULAR-ECONOMY IMPLICATIONS

The principal sustainability advantage of SS–RHA geopolymeric stabilization is simultaneous waste valorization. Gold mine tailings become a construction resource rather than a storage liability, steel slag is diverted from stockpiles and rice husk ash is converted from an agricultural residue into a reactive construction component. This supports circular-economy principles by substituting secondary resources for virgin materials and reducing dependence on conventional binders.
The effective reuse of gold mine tailings, steel slag and rice husk ash is in line with SDG 6, waste-derived infrastructure with SDG 9, sustainable urban infrastructure and pollution reduction with SDG 11, resource efficiency with SDG 12, and lower-emission construction pathways with SDG 13.

### 12.1 Carbon and Energy Considerations

Geopolymeric binders are often promoted as lower-carbon alternatives to Portland cement, but the environmental advantage is system-dependent. NaOH and sodium silicate have embodied energy and emissions, while transport, grinding and heat treatment of waste materials can also be important. Future studies should calculate cradle-to-gate and preferably cradle-to-site carbon intensity using local transport distances, electricity sources, activator production data and binder dosage. Waste utilization should therefore not automatically be equated with zero environmental burden.

## 13. COMPARATIVE SYNTHESIS OF STABILIZATION STRATEGIES

Different stabilization methods have been used to improve the engineering properties of gold mine tailings, but each approach has its own benefits and limitations as shown in Table 2. Traditional stabilizers such as cement and lime are effective in improving strength, plasticity, and bearing capacity, although their production can involve high costs and considerable environmental impacts. This has increased interest in using industrial and agricultural wastes, such as steel slag and rice husk ash, as alternative stabilizing materials. Steel slag provides calcium-rich components, while rice husk ash is rich in silica, and their combination under alkaline conditions can promote the formation of cementitious binding products. Comparing these approaches provides a basis for assessing whether alkaline-activated steel slag–rice husk ash can provide the required engineering improvement while making better use of locally available waste materials

Table 2. Comparative synthesis of stabilization strategies

| Strategy | Primary mechanism | Strength potential | Environmental function | Key limitation |
|---|---|---|---|---|
| Untreated GMT | Particle contact only | Low to moderate | No active immobilisation | Potentially unsuitable strength/plasticity and contaminant release |
| Cement-stabilized GMT | Hydration and cementitious bonding | High | Physical encapsulation; alkaline environment | Cement carbon footprint and cost |
| RHA-stabilized soil | Pozzolanic/reaction and filler effects | Moderate; dosage-dependent | Waste diversion | Low density; high water demand at high RHA |
| Steel-slag-stabilized soil | Packing, interlocking and calcium reactions | Moderate to high | Waste diversion; possible immobilisation | Expansion and source variability |
| SS–RHA alkaline-activated GMT | Dissolution + gel formation + packing | High potential | Waste valorisation + contaminant immobilisation | Activator burden, curing and source-specific optimization |

## 14. RESEARCH GAPS AND FUTURE DIRECTIONS

Although several studies have explored the use of different stabilizing materials for improving mine tailings, there is still limited information on the combined use of alkaline-activated steel slag and rice husk ash for gold mine tailings, especially in Nigeria as explained in Table 3. Most existing studies have focused mainly on strength improvement, with less attention given to the combined effects of strength, permeability, durability, environmental safety, cost, and sustainability. There is also a need to determine the most suitable proportion of steel slag and rice husk ash rather than relying on trial-and-error mixtures. Future studies should therefore investigate the long-term durability and leaching behaviour of the stabilized tailings and validate the optimized mixture through field trials to establish its suitability for practical road construction.

Table 3: Research gap and future directions

| Research gap | Importance | Recommended direction |
|---|---|---|
| Source variability | GMT, SS and RHA chemistry varies by site and process | Develop source-specific acceptance criteria using chemistry and mineralogy |
| Reactive versus total oxides | XRF totals do not equal reactive fraction | Combine XRF, XRD, FTIR and amorphous-phase/dissolution assessment |
| Activator environmental burden | Alkaline activators can carry substantial embodied impact | Investigate one-part and lower-alkali systems |
| Long-term durability | 28-day strength does not establish field life | Wet–dry, cyclic loading, dimensional and long-term immersion tests |
| Leaching under variable pH | Field conditions may differ from neutral-water testing | Use standardized and pH-dependent leaching protocols |
| Field-scale validation | Laboratory specimens do not capture construction variability | Construct and monitor pilot road sections |
| Economic performance | Technical feasibility may not imply economic feasibility | Apply cost analysis, BCR, PCI and LCCA |
| Life-cycle impact | Burden may shift to activator manufacture or transport | Perform full LCA including carbon and energy |
| Mechanistic understanding | Performance is controlled by multi-scale reactions | Correlate SEM/EDS, XRD and FTIR with strength evolution |
| Specification | Universal optimum does not exist | Develop performance-based specifications for stabilized tailings |

## 15. THE MATERIALS–PROCESS–STRUCTURE–PERFORMANCE FRAMEWORK AND ROLE OF EACH PRECURSOR

The materials–process–structure–performance framework in Figure 1 shows how the properties of steel slag (SS), rice husk ash (RHA), and gold mine tailings are connected to the final performance of the stabilized material. The chemical and mineralogical characteristics of SS and RHA influence how they react during alkaline activation. During the process, the alkaline solution helps to dissolve the reactive components and promotes the formation of new binding products. These products improve the bonding between the tailing particles and modify the internal structure of the mixture. As a result, the treated tailings can show improvements in strength, bearing capacity, permeability, plasticity, and durability. The alkaline-activation process relies on the complementary roles of SS and RHA as shown in Figure 2 and Table 4. RHA provides a rich source of silica, while SS contributes calcium and other reactive components. When the materials are mixed with an alkaline activator, these components begin to dissolve and interact, leading to the formation of cementitious binding products. These products gradually bind the gold mine tailing particles together, fill some of the spaces between particles, and produce a denser and more stable soil matrix.

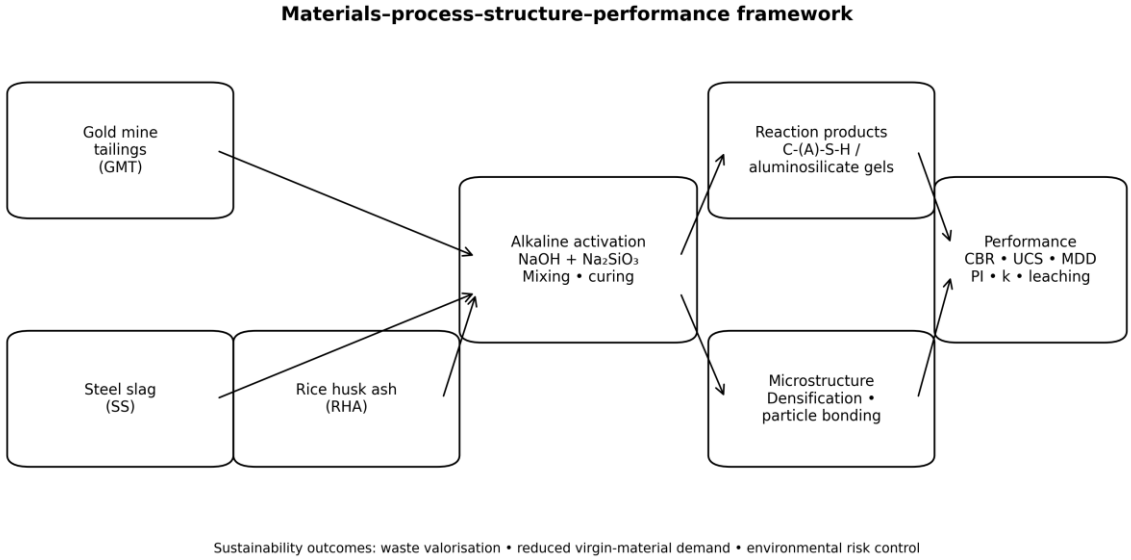



Figure 1. Materials–process–structure–performance framework for SS–RHA alkaline-activated stabilization of gold mine tailings.

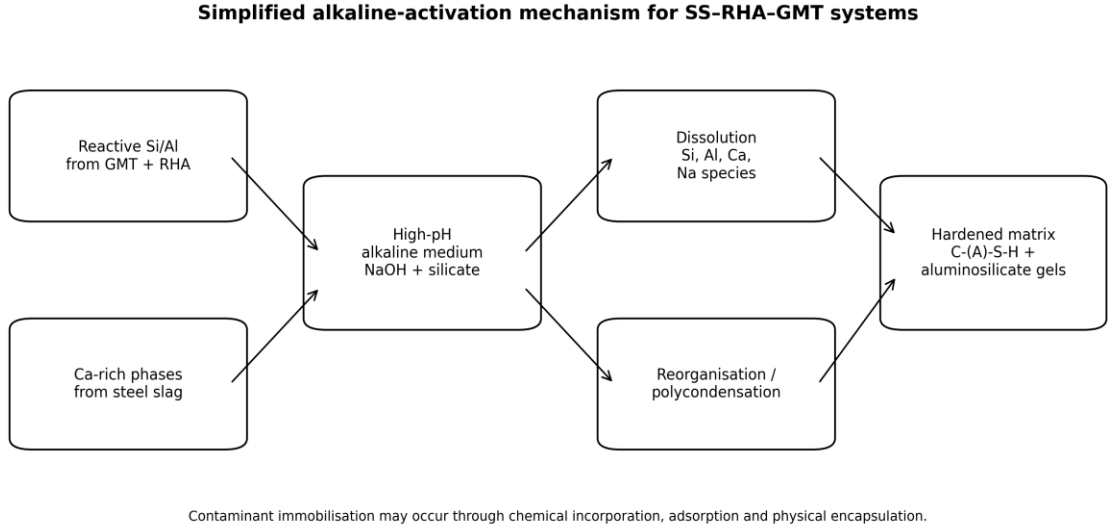



Figure 2. Simplified alkaline-activation mechanism showing complementary roles of silica/alumina and calcium-bearing precursors.

Table 4. Roles of major components in an SS–RHA geopolymeric stabilization system

| Component | Principal contribution | Potential limitation |
|---|---|---|
| Gold mine tailings | Target matrix; silica/alumina-bearing fraction; bulk material | Fine particles, variable mineralogy, potentially toxic elements and AMD-related risk |
| Steel slag | High-density angular particles; calcium/iron-bearing phases; improved packing | Free CaO/MgO and possible expansion; source-dependent chemistry |
| Rice husk ash | Silica-rich reactive precursor; fine filler | Low density, porous structure and increased water demand at excessive dosage |
| NaOH | High alkalinity and precursor dissolution | Caustic handling; excessive concentration can be detrimental |
| $Na_2SiO_3$ | Soluble silica and modified gel chemistry | Excess may shift Si/Al balance and reduce performance |
| Water | Mixing, transport and reaction medium | Excess increases porosity and may reduce strength |

## 16. PROPOSED DESIGN FRAMEWORK FOR ROAD APPLICATION

Based on the reviewed evidence, a practical development sequence for SS–RHA stabilization of GMT can be organized into seven stages:

(i) Material screening: determine particle size, specific gravity, XRF chemistry, XRD phases, FTIR functional groups and SEM/EDS morphology.
(ii) Precursor reactivity assessment: distinguish total oxide content from reactive or amorphous fractions and assess particle fineness.
(iii) Mixture design: establish feasible GMT–SS–RHA and activator ranges using an experimental design.
(iv) Engineering testing: measure Atterberg limits, MDD, OMC, unsoaked/soaked CBR, UCS at multiple curing ages and hydraulic conductivity.
(v) Environmental testing: conduct standardized leaching and pH assessments before and after stabilization.
(vi) Multi-response optimization: use RSM and desirability functions to identify a balanced formulation and validate it using independent specimens.
(vii) Field and sustainability validation: undertake pilot construction, monitor performance, quantify costs and complete life-cycle environmental assessment.

## 17. CONCLUSIONS

The literature demonstrates a strong technical rationale for combining steel slag and rice husk ash as complementary waste-derived constituents in alkaline-activated stabilization of mine tailings. Gold mine tailings provide the target matrix and may themselves contain useful silica and alumina, but environmental and engineering limitations can prevent direct pavement use. Steel slag contributes density, angularity and calcium-bearing phases, while RHA contributes reactive silica. Under alkaline activation, these constituents can participate in the development of binding products that improve particle bonding, strength and contaminant immobilization.

The principal lesson from the reviewed studies is that performance is governed by interaction rather than by the amount of any single additive. Steel slag dosage, RHA content, activator concentration, sodium silicate-to-NaOH ratio, water content, particle size and curing conditions must be optimized together. Excessive RHA can reduce density and increase water demand, excessive alkalinity can be counterproductive, and unconditioned steel slag can present expansion concerns.

Overall, alkaline-activated SS–RHA geopolymerization represents a promising pathway for converting locally available mining, metallurgical and agricultural wastes into functional pavement materials. The most important research priority is to move from laboratory demonstrations toward standardized, performance-based and life-cycle-informed design procedures suitable for Nigerian road construction conditions.

## REFERENCES

[1] Almeida, J., Ribeiro, A.B., Santos Silva, A., Faria, P. “Overview of mining residues incorporation in construction materials and barriers for full-scale application.” Journal of Building Engineering, Volume 29, 2020, Article 101215. doi: 10.1016/j.jobe.2020.101215.
[2] Laker, M.C. “Environmental impacts of gold mining—with special reference to South Africa.” Mining, Volume 3, Number 2, 2023, pp. 205–220. doi: 10.3390/mining3020012.
[3] Lindsay, M.B.J., Moncur, M.C., Bain, J.G., Jambor, J.L., Ptacek, C.J., and Blowes, D.W. “Geochemical and mineralogical aspects of sulfide mine tailings.” Applied Geochemistry, Volume 57, 2015, pp. 157–177. doi: 10.1016/j.apgeochem.2015.01.009.
[4] Kumkrong, P., Dy, E., Tyo, D.D., Jiang, C., Pihilligawa, I.G., Kingston, D., and Mercier, P.H.J. “Investigation of metal mobility in gold and silver mine tailings by single-step and sequential extractions.” Environmental Monitoring and Assessment, Volume 194, 2022, Article 423. doi: 10.1007/s10661-022-10054-3.
[5] Oluremi, J.R. and Ogundele, B.B. “Stabilization of Crude Oil Contaminated Lateritic Soil Using Composite Mixture of Biochar and Cement.” Uniosun Journal of Engineering and Environmental Sciences (UJEES), Volume 8, Number 1, 2026. doi: 10.64980/ujees.v8i1.001.
[6] Jaja, G.W.T. and Tamunoemi, A.L. “Stabilization of lateritic soils using steel slag.” Journal of Architecture and Civil Engineering, Volume 7, Number 2, 2022, pp. 7–16.
[7] Alhassan, M. and Mustapha, A.M. “Effect of rice husk ash on cement stabilized laterite.” Leonardo Electronic Journal of Practices and Technologies, Volume 11, 2007, pp. 47–58.
[8] Siddika, A., Mamun, M.A.A., Alyousef, R., and Mohammad Hosseini, H. “State-of-the-art review on rice husk ash: A supplementary cementitious material in concrete.” Journal of King Saud University – Engineering Sciences, Volume 33, 2021, pp. 294–307. doi: 10.1016/j.jksues.2020.10.006.

[9] Ahmari, S. and Zhang, L. "Durability and leaching behavior of mine tailings-based geopolymer bricks." Construction and Building Materials, Volume 44, 2013, pp. 743–750. doi: 10.1016/j.conbuildmat.2013.03.075.

[10] Provis, J.L., Palomo, A., and Shi, C. "Advances in understanding alkali-activated materials." Cement and Concrete Research, Volume 78, 2015, pp. 110–125. doi: 10.1016/j.cemconres.2015.04.013.

[11] Castillo, H., Collado, H., Droguett, T., Sánchez, S., Vesely, M., Garrido, P., and Palma, S. "Factors affecting the compressive strength of geopolymers: A review." Minerals, Volume 11, Number 12, 2021, Article 1317. doi: 10.3390/min11121317.

[12] Nehdi, M. and Tariq, A. "Stabilization of sulphidic mine tailings for prevention of metal release and acid drainage using cementitious materials: A review." Journal of Environmental Engineering and Science, Volume 6, Number 4, 2007, pp. 423–436. doi: 10.1139/s06-060.

[13] Saedi, A., Jamshidi-Zanjani, A., and Darban, A.K. "A review on different methods of activating tailings to improve their cementitious property as cemented paste and reusability." Journal of Environmental Management, Volume 270, 2020, Article 110881.

[14] He, X., Zhao, Y., Qaidi, S.M.A., Isleem, H.F., Zaid, O., Althoey, F., and Ahmad, J. "Mine tailings-based geopolymers: A comprehensive review." Ceramics International, Volume 48, Number 17, 2022, pp. 24192–24212. doi: 10.1016/j.ceramint.2022.05.345.

[15] Ahmari, S., Parameswaran, K., and Zhang, L. "Alkali activation of copper mine tailings and low-calcium flash-furnace copper smelter slag." Journal of Materials in Civil Engineering, Volume 27, 2015, Article 04014193.

[16] Manjarrez, L., Nikvar-Hassani, A., Shadnia, R., and Zhang, L. "Experimental study of geopolymer binder synthesized with copper mine tailings and low-calcium copper slag." Journal of Materials in Civil Engineering, Volume 31, Number 8, 2019, Article 04019156. doi: 10.1061/(ASCE)MT.1943-5533.0002808.

[17] Mashifana, T., Sebothoma, J., and Sithole, T. "Alkaline activation of basic oxygen furnace slag modified gold mine tailings for building material." Advances in Civil Engineering, Volume 2021, 2021, Article 9984494. doi: 10.1155/2021/9984494.

[18] Akinwumi, I., Adeyeri, J.B., and Ejohwomu, O. "Effects of steel slag addition on the plasticity, strength, and permeability of lateritic soil." In Proceedings of the International Conference on Sustainable Design, Engineering, and Construction, 2012, pp. 457–464. American Society of Civil Engineers. doi: 10.1061/9780784412688.055.

[19] Oluwasola, E.A., Afolayan, A., Popoola, M.O., and Afolabi, A.A. "Effect of steel slag on engineering properties of lateritic soil." American Journal of Engineering Research, Volume 9, Number 6, 2020, pp. 20–27.

[20] Abiodun, Y.O. and Jimoh, A.A. "Microstructural characterisation, physical and chemical properties of rice husk ash as viable pozzolan in building material: A case study of some Nigerian grown rice varieties." Nigerian Journal of Technology, Volume 37, Number 1, 2018, pp. 71–77. doi: 10.4314/njt.v37i1.10.

[21] Ayodele, A.L., Ajibola, I.K., and Fajobi, A.B. "Impact of rice husk ash based-geopolymer on some geotechnical properties of selected residual tropical soils." Nigerian Journal of Technology Development, Volume 21, Number 2, 2024. doi: 10.63746/njtd.v21i2.2417.

[22] Cai, D., Ouyang, M., Bao, X., Zhang, Q., Bi, Z., Yan, H., Li, S., Shi, Y. "Performance evaluation of stabilized soils with selected common waste materials of rice husk ash, steel slag and iron tailing powder." Materials, Volume 18, Number 2, 2025, Article 346. doi: 10.3390/ma18020346.

[23] Kang, X., Li, C., Zhang, M., Yu, X., Chen, Y. "Mechanical properties and stabilization mechanism of steel slag-rice husk ash solidified high plasticity clay." Geotechnical Testing Journal, Volume 47, Number 1, 2023. doi: 10.1520/GTJ20220294.

[24] Pan, Z., Hu, S., Zhang, C., Zhou, T., Hua, G., Li, Y., and Lv, X. "Mechanical and hydration characteristics of stabilized gold mine tailings using a sustainable industrial waste-based binder." Materials, Volume 16, Number 2, 2023, Article 634. doi: 10.3390/ma16020634.

[25] Gao, Y., Zhu, Z., Zhu, J., and Hu, X. "Study on the mechanical properties and water stability of steel slag-fly ash geopolymer for base stabilization." International Journal of Pavement Engineering, Volume 25, Number 1, 2024. doi: 10.1080/10298436.2024.2308168.

[26] Ikotun, J.O., Aderinto, G.E., Madirisha, M.M., and Katte, V.Y. "Geopolymer cement in pavement applications: Bridging sustainability and performance." Sustainability, Volume 16, Number 13, 2024, Article 5417. doi: 10.3390/su16135417.

[27] Levandoski, W.M.K., Mota, J.D., Menegolla, C., Ferrazzo, S.T., Bruschi, G.J., and Korf, E.P. "Mechanical strength, mineralogical characteristics and leaching behavior of iron ore tailings stabilized with alkali-activated rice husk ash and eggshell lime binder." Minerals, Volume 15, Number 6, 2025, Article 567. doi: 10.3390/min15060567.

[28] Blayi, R.A., Kakrasul, J.I., and Hamad, S.M. "An overview of rice husk ash as a waste by-product material for sustainable soil stabilization." Cleaner Waste Systems, Volume 12, 2025, Article 100446. doi: 10.1016/j.clwas.2025.100446.

[29] Wijesingha, A. and Eisazadeh, A. "Sustainable stabilization of fine-grained soils using lime, rice husk ash, bottom ash, and coir fiber: A comprehensive review." Engineering Journal, Volume 30, Number 2, 2026, pp. 13–41. doi: 10.4186/ej.2026.30.2.13.

[30] Van Deventer, J.S.J., Provis, J.L., Duxson, P., and Lukey, G.C. "Technical and commercial progress in the adoption of geopolymer technology." Minerals Engineering, Volume 20, 2007, pp. 1183–1190.

[31] Abdullah, M.M.A.B., Kamarudin, H., Nizar, I.K., Bnhussain, M., Zarina, Y., and Rafiza, A. "Correlation between Na2SiO3/NaOH ratio and fly ash/alkaline activator ratio to the strength of geopolymer." Advanced Materials Research, Volume 341–342, 2011, pp. 189–193.

[32] Pavithra, P., Reddy, M.S., Dinakar, P., Rao, B.H., Satpathy, B.K., and Mohanty, A.N. "Effect of the Na2SiO3/NaOH ratio and NaOH molarity on the synthesis of fly ash-based geopolymer mortar." In Proceedings of Geo-Chicago, 2016, pp. 336–344.

[33] Kwek, S.Y., Awang, H., and Cheah, C.B. "Influence of liquid-to-solid and alkaline activator ratios on fresh and hardened properties of alkaline-activated palm oil fuel ash geopolymer." Materials, Volume 14, Number 15, 2021, Article 4253. doi: 10.3390/ma14154253.

[34] Lahoti, M., Narang, P., Tan, K.H., and Yang, E.H. "Mix design factors and strength prediction of metakaolin-based geopolymer." Ceramics International, Volume 43, 2017, pp. 11433–11441.

[35] Xie, J. and Kayali, O. "Effect of initial water content and curing moisture conditions on the development of fly ash-based geopolymers in heat and ambient temperature." Construction and Building Materials, Volume 67, 2014, pp. 20–28. doi: 10.1016/j.conbuildmat.2013.10.047.

[36] Federal Ministry of Works and Housing (FMWH). (2016). General Specifications for Roads and Bridges. Federal Ministry of Works and Housing, Abuja, Nigeria.