

GEOTECHNICAL AND GEOCHEMICAL ANALYSIS OF ARTISANAL MINE WASTE AT AYANFURI: IMPLICATIONS FOR UTILISATION AS CONSTRUCTION MATERIALS

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Abstract

This study investigates the geotechnical and geochemical properties of artisanal mine waste originating from Ayanfuri, central Ghana, to rigorously assess its potential for reuse as a sustainable construction material. Artisanal and Small-Scale Mining (ASM) is a significant economic activity in the region, but it generates vast, uncontained volumes of tailings that represent a considerable long-term environmental liability and pose public health risks. The urgent need for efficient use of these mine wastes necessitates a comprehensive material characterisation study. Samples were systematically collected from five distinct disposal pits and subjected to a suite of laboratory analyses. Geotechnical tests included particle size distribution, specific gravity (SG), and constant-head permeability, which are crucial for determining structural viability and mechanical behaviour. Geochemical analyses measured pH, major soluble anions (chloride and sulphate), and total concentrations of heavy metals, including mercury (Hg) and arsenic (As). The results indicate that the waste is predominantly sand-sized, with coefficients of uniformity and curvature confirming it is a relatively well-graded material, suggesting high compaction potential. High SG values (2.64 to 2.69) reflect dense aggregates, and high permeability rates (0.30 to 0.46 cm/s) indicate excellent drainage characteristics. Geochemical tests showed a neutral to slightly acidic pH (6.06 to 6.53) and low chloride (<20 mg/kg) and sulphate (<80 mg/kg) levels within permissible limits. Crucially, however, concentrations of the toxic heavy metals, particularly arsenic (peaking above 180 mg/kg) and mercury, were found to be highly elevated in several samples. The study finds that, while the geotechnical properties are highly favourable for construction, the extensive arsenic and mercury contamination presents an unacceptable environmental risk, rendering the material unsuitable for direct reuse unless substantial stabilization and immobilization treatment is implemented.

Keywords

Artisanal Mine Waste, Geotechnical and Geochemical Properties, Arsenic and Mercury Contamination

Introduction

Artisanal and Small-scale Mining (ASM) represents a labour-intensive and low-capital form of mineral exploitation, characterised by simplified methods of exploration, extraction, processing, and transportation (Girard et al., 2022). Across Africa, artisanal and small-scale mining (ASM) dominates, occurring both underground through shallow shafts and along riverbeds and alluvial deposits (Bansah et al., 2017; Nurjaman et al., 2024; Zvarivadza, 2018). ASM has become a crucial livelihood strategy, providing income for tens of millions of individuals globally and involving men, women, and sometimes children working in groups of varying sizes (Armah et al., 2016; Geenen et al., 2021). Extraction methods are rudimentary, relying on picks, shovels, and small dredges, followed by manual grinding, gravity concentration, and amalgamation with mercury (Hinton et al., 2003; Seccatore et al., 2014). Although gravity concentration techniques help reduce mercury use (Martinez et al., 2021), mercury amalgamation and cyanidation remain widespread. These methods increase gold recovery but introduce significant environmental risks through mercury pollution and cyanide contamination (Eugene and Mujumdar, 2009; Ilyas and Lee, 2018; Torkaman and Veiga, 2023).

A major by-product of ASM and large-scale mining is overburden waste, which consists of soil and rock removed to

access valuable minerals (Siswanto et al., 2012). In opencast mining, this waste is often piled into large dumps, leading to severe environmental degradation, including water contamination during rainy seasons and dust pollution in dry conditions (Kuter, 2013; Minnaar, 2020; Richard and Odubo, 2024). Despite these hazards, overburden has acquired increasing economic potential. Many miners re-excavate dumps to recover residual gold or sell waste material to operators with better processing capacity, creating an informal waste-derived market (Jawadand and Randive, 2021; Kumah et al., 2020; Mishra et al., 2024). Technological developments such as mechanical crushers, ball mills, and centrifugal processors have enhanced mineral recovery and reduced waste volumes (Yilmaz, 2011). However, disparities in access to such technologies reinforce inequities within mining communities, as owners of cyanide processing plants exert control over who benefits from advanced recovery techniques, often marginalising poorer miners (Suhadi et al., 2021). Tailings, the fine-grained solid residues after ore processing, pose even greater environmental and health risks. Unlike large-scale mines that often contain tailings in engineered dams, ASM sites typically dump tailings openly, leaving them rich in mercury, sulphides, copper, and unrecovered gold (Cucciuto et al., 2023; Esdaile and Chalker, 2018; Kossoff et al., 2014). While advanced metallurgical methods such as cyanide leaching

and bioleaching provide opportunities for reprocessing and resource efficiency (Karimova et al., 2024; Vakilchap et al., 2020), tailings also contain silica, which when airborne contributes to silicosis and other respiratory diseases (He et al., 2022; Vanka et al., 2022). Toxic heavy metals such as arsenic, lead, cadmium, and zinc further contaminate soil and water, causing severe health impacts ranging from cancer to neurological and kidney disorders, while simultaneously disrupting ecosystems (Akhavan and Golchin, 2024; Karaca et al., 2018; Obasi and Akudinobi, 2020; Okewale and Grobler, 2023). These pollutants illustrate the double-edged nature of ASM tailings: while offering economic potential for reprocessing, they represent a critical source of environmental degradation and health risk if unmanaged.

Interestingly, Ghanaian mine tailings possess mineralogical characteristics suitable for beneficial reuse. Studies have revealed that crystalline quartz and aluminosilicate phases within tailings can serve as precursors for geopolymer and cementitious materials, thereby transforming a waste hazard into a resource (Cobbina et al., 2021; Kumi-Boateng, 2007). At the same time, water plays a central role in ASM, being essential for ore washing, processing, and dust control, yet it also functions as a pathway for contamination. Hydrochemical parameters such as turbidity, mineralisation, and pH are key indicators of mine water pollution (Arefieva et al., 2016; Jankowski et al., 2005). Contaminated mine water not only reduces water quality but destabilises groundwater systems, mobilising heavy metals and hydrocarbons that threaten both ecosystems and human populations (Castro et al., 2022; Olalekan et al., 2022; Zhang et al., 2024). To mitigate such impacts, a range of treatment methods including sedimentation, filtration, chemical precipitation, and membrane technologies have been proposed, alongside preventive upstream and remedial downstream approaches (Coudert et al., 2020; Jain and Das, 2017). Together, these dynamics show that although ASM provides vital socio-economic benefits, it also generates serious environmental, social and health challenges. Addressing this requires the urgent implementation of sustainable waste and water management solutions.

To determine its suitability and environmental acceptability, this study is designed with two core objectives: first, to assess the geotechnical properties of the artisanal mine waste to validate its structural performance, mechanical strength, and stability for use as a construction aggregate; and second, to critically evaluate the geochemical properties of the material to ensure its long-term inertness and mitigate potential risks associated with acid mine drainage, heavy metal mobility, and leaching when utilized in engineering applications.

Study Area

Location, Vegetation and Climate

Ayanfuri is a mining town located in the Upper Denkyira West District of Ghana's Central Region (Figure 1), with geographical coordinates of 5.9642° N and 1.8953° W and a land area of about 94 km² (Ewusi et al., 2023). It is surrounded by

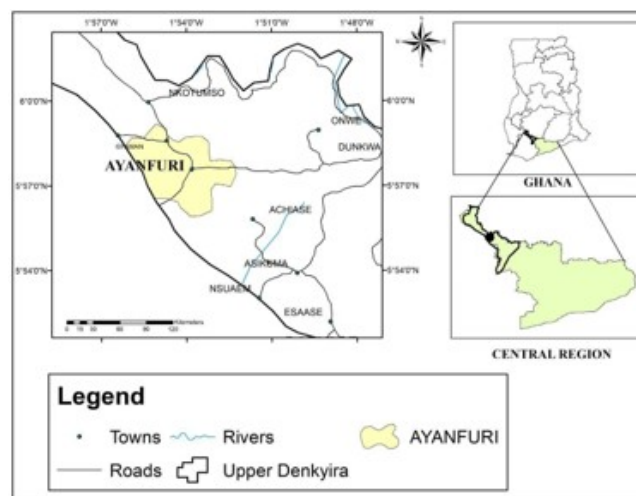


Figure 1. Map of Upper Denkyira West showing the Location of Study Area

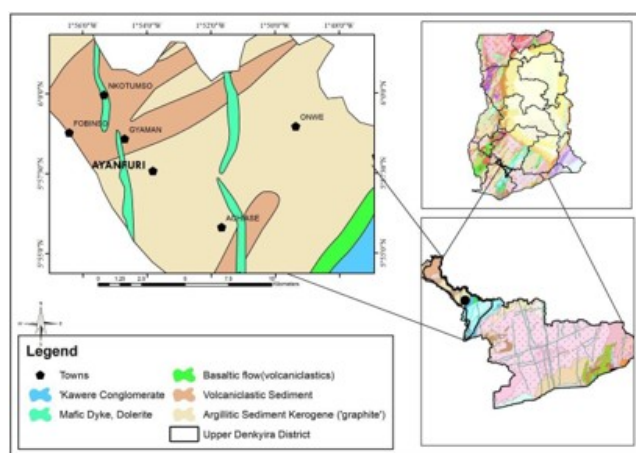


Figure 2. Geological Map of Ayanfuri

several communities, including Dunkwa-on-Offin to the north, Twifo Praso to the south, Obuasi to the east, and Bibiani to the west, with nearby towns such as Nkotumso, Dominase, and Diaso (Adu, 2018). The area has a tropical savanna climate, characterised by a wet season from April to October and a dry season from November to March, with harmattan winds influencing conditions in the latter. Its hilly and undulating terrain supports seasonal rivers and streams, most notably the Offin River, which flows into the Pra River (Addah, 2014; Faanu et al., 2024). Soils are dominated by forest ochrosols, laterites, and alluvials (Duncan, 2019), while vegetation is a mix of secondary forest, cultivated land, and degraded areas due to agriculture, logging, and mining (Acheampong et al., 2019).

Geology

Geologically, Ayanfuri lies within the Kumasi Basin on the western flank of the Ashanti Greenstone Belt, part of the Paleoproterozoic Birimian Supergroup of southwestern Ghana (Agbenyezi et al., 2022a). The Birimian rocks, metamorphosed under greenschist facies during the Eburnean orogeny (2.1 Ga), comprise metasedimentary units such as greywackes and

argillaceous sediments, alongside metavolcanics including basalt, dacite, and rhyolite (Ewusi et al., 2023; Wilson et al., 2022). These rocks display alternating anticline-structured sedimentary basins and syncline-structured volcanic belts with ENE–NE striking bedding surfaces, often reoriented near fold hinges and shear zones (Agbenyezi et al., 2022b). The dendritic drainage pattern of the terrain further influences seasonal water flow, which is often affected by mining activity.

Ayanfuri is part of the Ashanti Gold Belt, one of the world's most prolific gold-producing regions (Kuma et al., 2010). Gold mineralisation is primarily lode-type, hosted in quartz veins and shear zones within Birimian rocks and associated with sulphide minerals such as pyrite and arsenopyrite (Hayford et al., 2013; Sakyi et al., 2020). Granitoid intrusions also contribute to gold mineralisation, while significant alluvial deposits occur in riverbeds as a result of erosion and weathering of primary lode deposits (Kazapoe et al., 2023). These geological and geomorphological characteristics have made Ayanfuri a focal point of mining in Ghana, with both large-scale and artisanal operations exploiting its rich gold resources.

Materials and Methods

Samples

The tailings samples were collected from five pits (one sample from each pit) within the artisanal mine site at Ayanfuri using the random sampling method (Figure 3). A shovel was employed to collect the representative materials, which were immediately stored in labelled sample bags and transported to the Geotechnical and Environmental Laboratories of the University of Mines and Technology (UMaT), Tarkwa, for analysis. The laboratory investigations included both geotechnical and chemical testing, namely particle size distribution, specific gravity, permeability, pH, chloride, sulphate, and heavy metal determination. Before testing, the samples were air-dried, homogenized, and reduced in size using the cone and quartering technique to ensure representativeness.

Geotechnical properties

Grain size distribution was carried out using sieve analysis to characterize particle gradation as described in BS 1377-2 (Anderson, 2007). The oven-dried samples from pits 1–5 were weighed and passed through a stack of sieves arranged in decreasing aperture sizes, from 75 mm to 0.075 mm, with a pan at the bottom to collect fines. The sieve stack was shaken for 6–7 minutes, using the mechanical shaker at a frequency of 50 Hz, after which the retained mass on each sieve was recorded. The percentage retained was calculated as:

$$\text{Percentage Retained on each sieve} = \frac{M_R}{M_T} \times 100 \quad (1)$$

where M_R = mass retained (g) and M_T = total sample mass (g). From the particle size distribution curve, the coefficient of uniformity (C_u) and coefficient of curvature (C_c) were determined

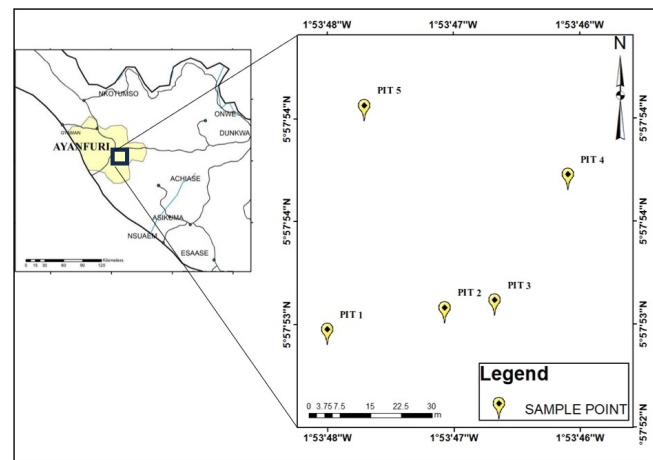


Figure 3. Map of Sampling Points

using Equations 2 and 3 respectively:

$$C_u = \frac{D_{60}}{D_{10}} \quad (2)$$

$$C_c = \frac{(D_{30})^2}{(D_{60} \times D_{10})} \quad (3)$$

with D_{10} , D_{30} and D_{60} representing the particle diameters at 10%, 30%, and 60% finer, respectively. A soil with $C_u < 3$ is uniformly graded, while $C_u > 5$ denotes well-graded soils; most well-graded soils present C_c values between 1 and 3. Specific gravity was measured using the density bottle method as described in ASTM D854-06 (Prakash et al., 2012). Three dried density bottles with stoppers were weighed (M_1), after which approximately 12.5 g of <2 mm soil fraction was introduced into each bottle and weighed again (M_2). Distilled water was added, bubbles were removed by gentle shaking, and the bottles were filled to the brim before being weighed (M_3). Finally, the bottles were filled with only distilled water and weighed (M_4). The specific gravity (G) was calculated using Equation 4:

$$G = \frac{(M_2 - M_1)}{(M_4 - M_1) - (M_3 - M_2)} \quad (4)$$

where M_1 = mass of bottle, M_2 = mass of bottle + dry soil, M_3 = mass of bottle + soil + water, and M_4 = mass of bottle + water.

Permeability was determined using the constant head method, where compacted specimens were subjected to steady water flow until equilibrium was achieved. The hydraulic gradient (I) was expressed as Equation 5:

$$I = \frac{(h_1 - h_2)}{y} \quad (5)$$

where $h_1 - h_2$ is the head loss across the sample and y is specimen length. The coefficient of permeability (K) was

calculated using Equation 6:

$$K = \frac{Q}{I \times A} \quad (6)$$

where Q = flow rate (R/t), R = volume of water collected, t = time, I = hydraulic gradient, and A = cross-sectional area.

Geochemical properties

The chemical analyses included pH, chloride, and sulphate determinations. For the pH test, 50 g of soil was mixed with 100 ml of distilled water, allowed to equilibrate for 15 minutes, and measured using a direct soil pH meter (Model HI 99121). Chloride concentration was measured using a Hydro Test HT 1000 photometer. A 230 g soil sample was mixed with 150 ml distilled water, shaken for 45 minutes, and allowed to settle. The supernatant was transferred into a 10 ml vial, treated with chloride reagent tablets (HT13 and HT14), and analysed photometrically after 2 minutes. Sulphate concentration was determined by dissolving a sulphate tablet in the filtrate and following the same procedure.

For heavy metal analysis, 5 g of each sample was digested with a mixture of concentrated hydrochloric acid and nitric acid at 120 °C for one hour. The digested solution was cooled, filtered, and analysed using Atomic Absorption Spectrometry (AAS). Mercury (Hg) and Arsenic (As) concentrations were specifically determined due to their environmental relevance in artisanal mining activities. These geotechnical and chemical tests collectively provided essential information on the engineering behavior and contamination potential of the mine tailings from Ayanfuri.

Results and Discussions

Geotechnical Properties

Particle Size Distribution

The particle size distribution (PSD) results for the five sampling pits were analyzed according to ASTM D422-63, with classifications carried out using the Unified Soil Classification System (USCS). The sieve analysis data provided effective particle sizes (D_{10} , D_{30} , D_{60}), which were used to calculate the uniformity coefficients (C_u) and curvature coefficients (C_c). The C_u values ranged from 4.24 to 5.71. Based on these results, the samples were classified as well-graded sands under the USCS system. This is because the C_u values are significantly greater than 1, and greater than the typical threshold of 4 or 6 used to define well-graded gravels and sands (respectively) as discussed in [Das and Sobhan \(2014\)](#). The C_c values fell within the range of 0.74 to 1.67. For a soil to be classified as well-graded (USCS), the C_c must satisfy the condition $1 \leq C_c \leq 3$. Since the majority of the samples are within or extremely close to this range (especially the upper limit of 1.67), this confirms a smooth and continuous gradation curve. The sample slightly below 1 (0.74) suggests a minor deficiency in certain intermediate particle sizes, but the overall trend confirms a well-graded material. The predominance of sand-sized particles with minimal silt or clay further confirmed

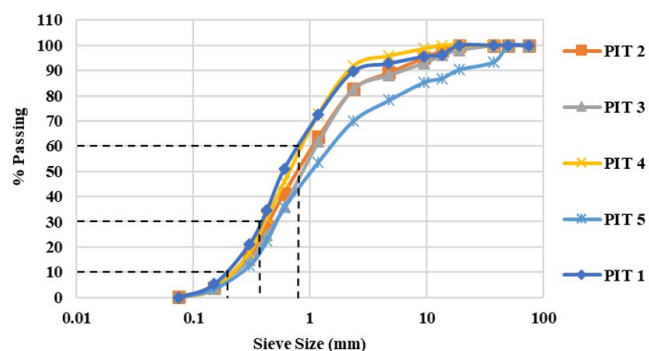


Figure 4. Graph Showing the Particle Size Distribution Curves

the well-graded nature of the tailings. Figure 4 provides a representative example of the particle size distribution curve, using data from Pit 1 to illustrate the graphical method used to determine the D_{10} , D_{30} and D_{60} diameters for all five sampled pits. Table 2 also summarizes the results obtained from the D_{10} , D_{30} and D_{60} variables and C_u , C_c parameters together with the respective classifications of the materials tested.

The well-graded nature of the tailings materials infers that smaller particles fill the voids between larger particles, allowing the material to achieve greater maximum dry density and stability when compacted. In addition, well-graded materials typically exhibit higher shear strength and better load-bearing capacity than poorly sorted (uniform) soils. The denser packing (due to gradation) generally leads to lower permeability, which is important for engineering structures like road bases and embankments, due to the ability of reducing water infiltration and settlement potential ([Das and Sobhan, 2014](#)).

Specific Gravity

The average specific gravity results revealed values ranging between 2.64 and 2.69, which virtually fall within the typical range for quartz-based sands (2.65–2.70). This indicates that the soils are predominantly sandy in nature, with minimal mineralogical variation across the different sampling pits [Ahmadi et al. \(2020\)](#); [Bowles \(2012\)](#). Such consistency suggests a uniform composition of the artisanal mine waste materials, likely derived from similar parent rock sources. The alignment of these values with standard construction sands indicates that the tailings can be considered suitable for various geotechnical applications, including use as fill material and, when properly blended, in concrete mixes. These findings demonstrate the potential for reusing mine wastes in engineering projects, reducing environmental impacts while providing construction materials, as summarized in Table 3.

Permeability Test

The permeability test results ranged from 0.30 to 0.46 cm/s, confirming that the soils are moderately to highly permeable sands. Pit 4 recorded the highest value (0.46 cm/s), suggesting coarser particles and superior drainage potential compared to the other pits. Pits 1, 3, and 5 showed similar values of about

Table 1. Thresholds for Test Parameters

Parameter	Threshold (Soils for Construction)	Reference
pH	6 – 8.5	BS 1377 (1990), ASTM D4972
Chlorides (Cl ⁻)	≤ 500 mg/kg (water-soluble)	BS 1377, BRE Digest 363
Sulphates (SO ₄ ²⁻)	< 2000 mg/kg (negligible); > 2000 mg/kg requires Sulphate-resisting concrete	BRE Digest 1, BS 8500
Mercury (Hg)	≤ 1 mg/kg (above this, soil is contaminated)	US EPA, Dutch Soil Standards, GSA
Arsenic (As)	≤ 10 mg/kg; ≤ 2 mg/kg	US EPA Soil Screening Levels; GSA

Note: GSA = Ghana Standards Authority; US EPA = United States Environmental Protection Agency.

Table 2. Results for Particle Size Distributions

Pit ID	D ₁₀	D ₃₀	D ₆₀	C _u	C _c	USCS Classification
1	0.20	0.40	0.80	4.44	1.00	Well-graded sand (SW)
2	0.11	0.45	1.10	5.23	1.67	Well-graded sand (SW)
3	0.22	0.52	1.20	5.45	1.02	Well-graded sand (SW)
4	0.21	0.45	0.89	4.24	1.08	Well-graded sand (SW)
5	0.24	0.52	1.60	5.71	0.74	Well-graded sand (SW)

Note: D₁₀, D₃₀, D₆₀ = particle diameters at 10%, 30%, and 60% finer (mm); C_u = coefficient of uniformity; C_c = coefficient of curvature; SW = well-graded sand.

Table 3. Results for Specific Gravity Test

Pit ID	Specific Gravity of Soil Sample		
	Replicate 1	Replicate 2	Average
1	2.65	2.65	2.65
2	2.63	2.65	2.64
3	2.68	2.68	2.68
4	2.69	2.69	2.69
5	2.66	2.64	2.65

Note: Specific gravity values fall within the typical range for quartz-based sands (2.65–2.70).

0.30 cm/s, indicating uniform sandy textures across these locations. Pit 2 had a slightly higher permeability of 0.36 cm/s, consistent with good drainage behavior. Overall, the values align with the expected range for sandy soils, confirming the suitability of these mine waste materials for geotechnical applications requiring effective drainage, as summarized in Table 4.

Geochemical Properties

The geochemical analysis involved the determination of pH, chloride (Cl⁻), sulphate (SO₄²⁻), and concentrations of heavy metals such as mercury (Hg) and arsenic (As). The tailings material is characterized by a narrow, slightly acidic range of pH values, averaging 6.29 across the five sampled pits. The most significant geochemical finding is the pervasive contamination by Arsenic (As), which recorded a high average concentration of 135.617 mg/kg and peaked at 183.554 mg/kg. Further assessment reveals notable Mercury (Hg) concentrations, averaging 3.682 mg/kg and reaching a substantial outlier value of 13.799 mg/kg in Pit 1, while major anions (Cl⁻ and SO₄²⁻) were generally low or moderate. The results from the five pits are shown in Table 5 with the thresholds for

each parameter in Table 1.

pH, Chloride and Sulphate

The mine waste pH ranged from 6.06 to 6.53, indicating slightly acidic to near-neutral conditions that may enhance heavy metal mobility. Chloride levels reached up to 19.5 mg/kg, while sulphate concentrations were as high as 84.99 mg/kg. Since these values for Chloride and Sulphate are way below the thresholds as depicted in Table 1 (500 mg/kg and 2000 mg/kg respectively), the materials could be said to be of no significant effect on the quality of construction materials. Elevated chloride can accelerate steel corrosion, and sulphate may trigger sulphate attack in cementitious materials. These findings suggest the untreated material would not negatively impact the durability of construction works.

Heavy Metals (Hg and As)

Mercury concentrations ranged from 0.24–13.80 mg/kg and Arsenic from 79.05–183.55 mg/kg, both above international safety standards. Previous studies in Ghana (Armah et al., 2016) attribute such enrichment to mercury amalgamation and arsenopyrite weathering in artisanal mining. These elevated levels present environmental and health risks, particularly through groundwater leaching and dust inhalation. Compared to EU inert waste criteria (As < 25 mg/kg, Hg < 1 mg/kg), the samples are far above acceptable limits. With respect to the Ghana Standards Authority also, as reported by Gbadago et al. (2025), the concentrations for Hg and As fall above the thresholds (≤ 1 mg/kg and ≤ 2 mg/kg respectively). Therefore, Ayanfuri mine waste is unsuitable for direct use in construction without remediation.

Conclusion

Geotechnical evaluation of the Ayanfuri mine waste revealed that the tailings material is predominantly composed of sand-

Table 4. Results for Permeability Test

Pit ID	Range of K (cm/s)	Average K (cm/s)	Interpretation
1	0.198 – 0.410	0.30	Moderately permeable; typical of uniform sand
2	0.293 – 0.530	0.36	Highly permeable; suitable for drainage applications
3	0.269 – 0.589	0.30	Moderately permeable; consistent with coarse sand
4	0.360 – 0.697	0.46	Very permeable; indicates coarse, well-draining sand
5	0.235 – 0.430	0.31	Moderately permeable; suitable for construction fills

Note: K = coefficient of permeability.

Table 5. Results for Geochemical Test Works

Pit ID	pH	Cl ⁻ (mg/kg)	SO ₄ ²⁻ (mg/kg)	Hg (mg/kg)	As (mg/kg)
1	6.53	19.50	74.99	13.799	135.589
2	6.46	< 0.5	< 5	3.514	79.059
3	6.06	9.50	84.99	0.475	183.554
4	6.27	< 0.5	79.98	0.383	182.660
5	6.11	< 0.5	< 5	0.238	97.221
Average	6.29	14.5	79.98	3.682	135.617

Note: Cl⁻ = chloride; SO₄²⁻ = sulphate; Hg = mercury; As = arsenic. Threshold values are provided in Table 1.

sized particles with traces of gravel and silt, and is generally well-graded. The specific gravity values, ranging from 2.64 to 2.69, indicate a dense and stable material consistent with quartz-based sands commonly used in construction. Permeability coefficients between 0.30 and 0.46 cm/s confirm the high drainage capacity of the mine waste materials, further supporting their suitability for geotechnical applications such as backfilling, road base, and other engineering works where stability and drainage are critical.

From a geochemical perspective, the pH values (6.06–6.53) indicate slightly acidic to near-neutral conditions that are generally safe for construction. Chloride and sulphate concentrations also fall within acceptable limits, reducing concerns over corrosion of steel reinforcement and sulphate attack in concrete. However, the detection of Mercury in Pits 1 and 2, exceeding the threshold of ≤ 1 mg/kg, and Arsenic concentrations above the limit of ≤ 10 mg/kg in all the pits, present a serious environmental and health hazard. These levels, which significantly surpass international inert waste criteria (for example, US EPA Soil Screening Levels, Ghana Standards Authority), indicate that the material poses a substantial risk for groundwater contamination through leaching and respiratory health risks from dust inhalation. Consequently, the tailings cannot be considered safe for direct engineering application without prior stabilisation or remediation to immobilise these toxic heavy metals.

Prior to any construction application, the mine waste with elevated mercury and arsenic concentrations must be stabilised using cement, lime, or other encapsulating agents to immobilise contaminants and minimise leaching, while simultaneously improving geotechnical performance (Kogbara, 2013). In addition, further assessments, including compressive strength, leachability, and long-term durability tests, are

necessary to validate the structural integrity and environmental safety of the treated material, thereby ensuring its suitability for sustainable engineering applications.

Implications for Utilisation

Although untreated mine waste from Ayanfuri is unsuitable for direct construction use, stabilisation methods offer a pathway for safe reuse. Previous Ghanaian studies, including that of (Acheampong et al., 2013) on lime stabilisation have demonstrated that adding lime or cement immobilises heavy metals by forming insoluble compounds while neutralising acidity. This treatment reduces leaching risks and enhances the geotechnical strength of the material, making it viable for applications such as bricks or road base. Therefore, safe utilisation requires solidification/stabilisation before use, supported by routine monitoring. The

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