

Sustainable utilization of gold mining tailings in concrete block production through solidification techniques

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ABSTRACT

In light of increasing environmental and health risks from gold mining tailings, this study investigates the use of detoxified tailings from PT Agincourt Resources in concrete block production via solidification/stabilization. Portland cement was blended with subsoil and tailings at varying ratios, and blocks were evaluated for compressive strength, water absorption, and leaching behavior (TCLP). The optimal cement–tailings mixture (1:1) attained 102.33 kg/cm² (Grade I), while the cement–subsoil–tailings blend (7:3) reached 68.32 kg/cm² (Grade II); both met durability and environmental safety criteria. These results demonstrate a novel circular-economy strategy that repurposes mining waste into structurally robust, eco-friendly construction materials. The approach offers potential for reducing cement consumption and heavy-metal leaching. Further research should explore long-term performance and industrial scalability to maximize environmental and economic benefits globally.

Keywords: compressive strength, environmental safety, gold mining tailings, leaching safety, solidification, sustainability.

INTRODUCTION

Gold mining significantly contributes to industrial and national economic growth worldwide. However, its extraction processes result in serious environmental and public health risks due to the release of toxic substances such as heavy metals and cyanide [1, 2]. Tailings – the residual waste from ore processing – often contain hazardous compounds including arsenic (As), cadmium (Cd), lead (Pb), mercury (Hg), and cyanide (CN), which severely impact surrounding soil and water systems [3,4]. These contaminants frequently exceed the limits set by the World Health Organization, raising major health concerns for communities near mining sites [5]. Improper disposal practices have been linked to long-term ecological damage and increased incidence of disease in affected regions [6, 7]. Therefore, effective waste management strategies and strong regulatory enforcement are urgently required to mitigate such risks [2].

Conventional tailings storage facilities (TSFs) are often unable to prevent heavy-metal leaching over time due to several factors, including structural degradation of containment barriers, cracks or breaches caused by differential settlement, inadequate liner systems, and prolonged exposure to rainfall and groundwater infiltration that facilitates contaminant migration [8]. In many cases, oxidation of sulfide minerals within tailings generates acidic leachate, further accelerating the mobilization of toxic metals. These limitations have prompted growing interest in solidification/stabilization (S/S) techniques using Portland cement to immobilize hazardous compounds [9,10]. Recent advances have explored supplementary cementitious materials (SCMs) derived from mining wastes: Adediran et al. (2025) demonstrated that high-alumina, high-magnesium, and high-silica mine tailings can function effectively as SCMs in Portland cement matrices, enhancing reactivity and early-age strength through optimized C–(A)–S–H formation. A parallel study [11] evaluated

these three tailings types in concrete, confirming improvements in compressive strength and durability, while also highlighting challenges in water resistance and binder compatibility. Further innovations have incorporated fly ash, nano-silica, and natural fibers; however, excessive SCM loading can compromise structural performance, and binder optimization remains critical [12–14]. Recent research has shown that gold mining tailings can be transformed into construction materials, particularly concrete blocks, through solidification processes. This approach not only immobilizes hazardous substances but also promotes resource recovery in line with circular economy principles [15, 16]. SCMs such as fly ash have been used to improve compressive strength and reduce the risk of alkali–silica reaction, a common durability issue in cementitious products [17,18]. Moreover, alternative binders like subsoil offer promising potential as low-cost substitutes for conventional pozzolans when combined with Portland cement [19]. In parallel, reducing clinker content in cement formulations remains essential for lowering carbon emissions in the construction sector [20, 21].

To address these gaps, this study builds on the limited body of research that integrates detoxified gold tailings with subsoil binders for concrete block production, an area where most previous works have focused only on single-type tailings or small-scale tests. Earlier studies have highlighted key obstacles, such as uncertainties in controlling water absorption, challenges in minimizing heavy-metal leaching, and difficulties in achieving optimal mechanical strength from mixed waste binders [22, 23]. These challenges underscore the need for full-scale evaluations to ensure both structural performance and environmental compliance. In response, this study assesses detoxified gold tailings from PT Agincourt Resources as a partial cement replacement – both alone and blended with subsoil in concrete blocks. Our objectives are to (i) optimize binder ratios for mechanical strength, (ii) evaluate water absorption and leaching behaviour to ensure environmental safety, and (iii) demonstrate the novelty of combining mining and subsoil wastes for sustainable, full-size construction materials. By directly addressing the technical and environmental limitations reported in prior studies, this work advances the state of the art by bridging laboratory findings to industrial applicability while reinforcing circular-economy principles.

MATERIALS AND METHODS

Research design

This experimental study was designed to evaluate the feasibility of incorporating gold mining tailings as a partial cement replacement in concrete block production via solidification/stabilization. The research framework comprised four sequential phases: (1) characterization of raw materials, (2) optimization of binder compositions, (3) preparation and curing of specimens, and (4) assessment of mechanical and environmental performance against relevant standard.

Materials

The primary materials used in this study included gold mining tailings, subsoil, Portland cement, and water. Gold mining tailings were sourced from a mining operation in Kabupaten Tapanuli Selatan, North Sumatra, and underwent detoxification using a lime-based neutralization process followed by sedimentation, in accordance with the Indonesian National Standard SNI 6989.57:2008 for reducing cyanide and heavy-metal content. The detoxified slurry was then mechanically pressed into a wet cake form for ease of handling and subsequent mixing. Subsoil was collected from the mining site's Tailings Management Facilities (TMF) development area. Portland cement was selected as the binding agent due to its well-established performance in solidification processes [9].

Experimental procedures

Material characterization

To assess material suitability, samples underwent comprehensive analyses including heavy metal concentrations (USEPA 3050B), moisture content (ASTM C566), particle size distribution (sieve and hydrometer analyses), bulk density (ASTM D2937), and oxide content (SiO_2 , Al_2O_3 , Fe_2O_3) following ASTM 2012. Table 1 presents the contaminant concentrations in tailings and subsoil, which remained below national regulatory thresholds.

Specimen preparation

Concrete specimens were prepared in two phases. In Phase I, Portland cement was blended separately with volcanic tuff soil (ST) and subsoil (SS) at ratios ranging from 1:9 to 9:1 (cement:pozzolan by mass) to identify the

Table 1. Chemical and physical properties of gold mining tailings and subsoil

No	Parameter	Concentration (mg/dry kg)		
		Tailing	Subsoil	Nasional quality standards
1	Arsenic (As)	408.3	86.9	500
2	Cadmium (Cd)	0.3	0	100
3	Hexagonal chromium (Cr ⁶⁺)	0.8	0	500
4	Copper (Cu)	72.7	69.8	3000
5	Lead (Pb)	209	61.9	1500
6	Mercury (Hg)	0.7	0.2	75
7	Molybdenum (Mo)	3.2	1.7	1000
8	Nickel (Ni)	8.7	16.8	3000
9	Selenium (Se)	8.3	1.5	50
10	Zinc (Zn)	38.3	38.5	3750

optimal cement efficiency. Mixtures were cast into $5 \times 5 \times 5$ cm molds in accordance with ASTM C109/C109M and cured for 28 days at 23 ± 2 °C and 95 ± 5 % relative humidity [24]. In Phase II, optimal binder formulations from Phase I were mixed with gold mining tailings at the same mass ratios to produce cement–subsoil–tailings (SSTG), cement–volcanic tuff–tailings (STTG), and cement–tailings (STG) specimens, which were similarly molded and cured. Full-size concrete blocks measuring $40 \times 20 \times 10$ cm were cast using the optimal SSTG (7:3) and STG (5:5) mixtures. Variations in composition and comparison of materials to make test object can be seen in Table 2.

Phase II introduced tailings into selected optimal binders to produce SSTG, STTG, and STG mixtures, also molded into $5 \times 5 \times 5$ cm specimens. Ratios are provided in Table 3.

Concrete blocks with dimensions of $40 \times 20 \times 10$ cm were produced using the optimal binder compositions identified in the specimen testing

phase. These blocks were subjected to mechanical and environmental performance

Mechanical performance testing

Compressive strength of the $5 \times 5 \times 5$ cm specimens and full-size blocks was measured with a universal testing machine (UTM) according to ASTM C39/C39M. The compressive strength, denoted as F_c , was calculated as the maximum load divided by the cross-sectional area, as shown in Equation 1:

$$F_c = \frac{P}{A} \quad (1)$$

where: F_c – compressive strength (kg/cm²),
 P – applied load (kg), A – cross-sectional area (cm²).

Water absorption was evaluated following ASTM C642 by comparing wet and dry weights of $40 \times 20 \times 10$ cm blocks to determine porosity and durability, using Equation 2:

Table 2. Binder composition ratios used for specimen preparation in Phase I

Composition variations	Mixture ST (g)		Mixture SS (g)	
	Portland cement	Volcanic tuff	Portland cement	Subsoil
1:9	20	180	20	180
2:8	40	160	40	160
3:7	60	140	60	140
4:6	80	120	80	120
5:5	100	100	100	100
6:4	120	80	120	80
7:3	140	60	140	60
8:2	160	40	160	40
9:1	180	20	180	20

Table 3. Binder composition ratios used for specimen preparation in Phase II

Composition variations	Mixture SSTG (g)		Mixture STTG (g)		Mixture STG (g)	
	SS	Tailing	ST	Tailing	Cement	Tailing
1:9	20	180	20	180	20	180
2:8	40	160	40	160	40	160
3:7	60	140	60	140	60	140
4:6	80	120	80	120	80	120
5:5	100	100	100	100	100	100
6:4	120	80	120	80	120	80
7:3	140	60	140	60	140	60
8:2	160	40	160	40	160	40
9:1	180	20	180	20	180	20

$$\text{Water Absorption (\%)} = \frac{A-B}{B} \times 100\% \quad (2)$$

where: A – wet weight (g), B – dry weight (g).

Environmental safety testing

Leachability of heavy metals from full-size blocks was assessed using the toxicity characteristic leaching procedure (TCLP) per U.S. EPA Method 1311 to ensure compliance with national environmental safety standards.

Data analysis

Experimental data were analyzed using statistical methods to determine the significance of binder composition on compressive strength, water absorption, and contaminant leachability. Comparative analysis of performance across varying compositions identified the optimal mixture for structural integrity and environmental safety. This comprehensive methodology ensures the systematic evaluation of gold mining tailings as a sustainable material for concrete block production, balancing mechanical performance with environmental responsibility.

RESULTS

Material characterization

Particle size distribution

The particle size distribution analysis revealed that 60% of gold mining tailings passed through a 0.075 mm sieve, classifying them as fine-grained soil according to USCS. In contrast,

subsoil displayed a coarser texture, with significant mass retained on larger sieves, indicating its potential as a stabilizing agent. The fine size of tailings promotes pozzolanic reactivity, contributing to improved mechanical strength through enhanced binder-particle interactions [26]. The results of the test of the size distribution of the Tailings test material can be seen in Table 4.

Moisture content

Gold mining tailings exhibited a high moisture content of 21.63%, exceeding ASTM recommended limits of 3–5%. In contrast, subsoil registered 4.78%, aligning with standards for cementitious use. High tailings moisture necessitated pre-drying to ensure effective cement hydration [27].

Chemical composition

The oxide composition analysis showed that tailings contained 75.97% SiO₂, 9.24% Al₂O₃, and 5.83% Fe₂O₃, while subsoil contained 45.75% SiO₂, 26.50% Al₂O₃, and 12.65% Fe₂O₃. The total oxide content for both materials exceeded 70%, confirming their pozzolanic potential. The results of oxide composition testing for tailings, subsoil, and volcanic tuff soil are presented in Table 5.

Mechanical performance

Phase I: Binder composition testing

Table 6 shows that the highest compressive strength for ST (cement–volcanic tuff soil) specimens was 114.7 kg/cm² (7:3), whereas SS (cement–subsoil) specimens achieved 127.3 kg/cm² (9:1). However, despite the slightly higher strength of the SS 9:1 mixture, the SS 7:3 mixture (109.3 kg/cm²) was selected as optimal because it provides

Table 4. Sieve analysis results showing the particle size distribution of gold mining tailings and subsoil

Sieving		Hydrometer	
Size (mm)	Passing (%)	Size (mm)	Passing (%)
75.000	100	0.0481	53
37.500	100	0.0347	46
19.000	100	0.0249	41
9.500	100	0.0173	34
4.750	100	0.0129	29
2.360	100	0.0099	26
1.180	100	0.0066	21
0.600	99	0.0047	17
0.425	98	0.0036	14
0.300	94	0.0024	10
0.150	77	0.0014	8
0.075	60	-	-

Table 5. Oxide composition of gold mining tailings and subsoil samples

Chemical composition	Concentration (%)		
	Tailing	Subsoil	Volcanic tuff soil
Aluminum oxide, Al_2O_3	9.24	26.50	11
Iron oxide, Fe_2O_3	5.83	12.65	35
Silicon dioxide, SiO_2	75.97	45.75	35.4
Total	91.04	84.90	81.4

comparable strength while significantly reducing cement usage, thereby improving material cost efficiency and lowering environmental impact through reduced clinker consumption. These results meet the Indonesian SNI 03-0349-1989 standard of 100 kg/cm² for Grade I concrete blocks.

The ST test specimen was completely destroyed immediately after being removed from the mold, rendering it unsuitable for compressive strength testing. In contrast, the SS test specimen exhibited good bonding with no composition variations showing signs of failure shown in Figure 1. The disintegration of the ST specimen at mixing ratios of 1:9 and 2:8 was attributed to the low alumina modulus of the volcanic tuff soil, which was only 0.314. This low alumina modulus adversely affected the early-age strength of the specimen. Conversely, the SS specimen demonstrated a higher alumina modulus of 2.094. This finding aligns with previous research indicating that increased aluminum content contributes to higher compressive strength.

It is noteworthy that at the 9:1 ratio, both ST and SS specimens exhibited visible surface cracking despite the difference in compressive strength

values, with SS showing higher resistance and ST showing lower resistance. This cracking is likely attributed to differential shrinkage during curing, where high cement content in SS increased early-age shrinkage stresses, while the lower binding capacity and poor particle packing of ST led to microstructural weaknesses. In both cases, thermal and moisture gradients during curing may have exacerbated tensile stresses, initiating crack formation. Binder testing results show that increased aluminum and cement content enhances compressive strength by promoting calcium silicate hydrate (C-S-H) formation through accelerated hydration reactions, aligning with previous studies [27–29]. The successful solidification mechanism is significantly influenced by the addition of pozzolans, such as fly ash and subsoil, which serve as alternative fine aggregates in the brick mixture. Natural pozzolans like fly ash enhance cement strength and density by reacting with calcium hydroxide to form additional C-S-H, as supported by several studies through their silica and alumina-driven pozzolanic activity [30–32]. Excessive silica content may reduce compressive strength, though evidence remains

Table 6. Compressive strength results of Phase I binders ($5 \times 5 \times 5$ cm specimens)

Composition variations	Compressive strength value (kg/cm ²)	
	ST	SS
1:9	0	0.2
2:8	0	3.59
3:7	0.2	25.04
4:6	2.9	42.26
5:5	17	23
6:4	49	94
7:3	114.7	109.3
8:2	78.5	112.9
9:1	65.3	127.3

context-dependent. While some studies suggest strength enhancement, others, like Childers et al. [33], focus on self-healing, and Guo et al. [34] report increased strength in non-concrete systems, limiting direct applicability to concrete mixtures. This highlights the critical balance required in pozzolan incorporation to optimize the mechanical properties of cement-based materials.

The determination of the optimal composition is not solely based on the test specimen with the highest compressive strength. It is also crucial to consider the efficient use of cement to avoid excessive consumption, thereby ensuring a more cost-effective solution, as illustrated in Figure 2. Additionally, selecting the optimal composition in the first stage of testing must account for the availability of lime required to sustain the pozzolanic reaction, ensuring the material's long-term performance and durability.

Based on the comparison between the two variables, it was observed that the ST specimen with a 7:3 composition ratio, using 140 grams of cement, achieved the highest compressive strength of 114.7 kg/cm². In contrast, the SS specimen exhibited its highest compressive strength at a 9:1 composition ratio with 180 grams of cement. However, this high cement usage is economically inefficient due to excessive material consumption. Therefore, for the SS specimen, the optimal composition was determined by balancing maximum compressive strength with minimal cement usage.

Considering these factors, the optimal composition for the SS specimen was identified at the 7:3 ratio, yielding a compressive strength of 109.3 kg/cm². This result complies with the Indonesian National Standard (SNI) 03-0349-1989 for grade 1 concrete blocks used in wall construction,

which requires a minimum compressive strength of 100 kg/cm². The selection of this composition ensures not only mechanical performance but also economic efficiency, making it a viable choice for practical applications in construction

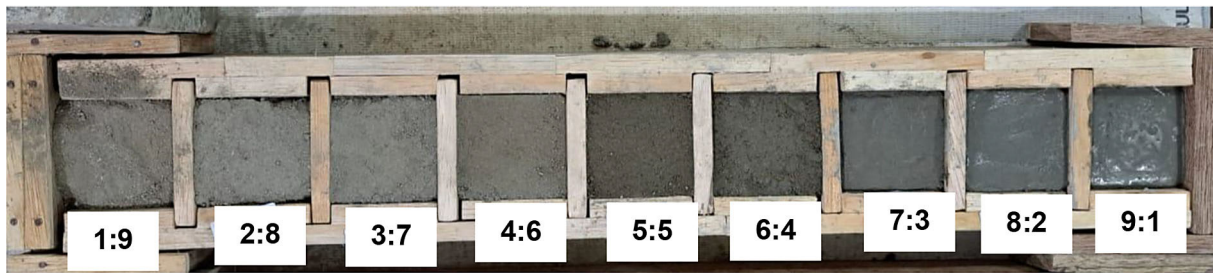
Phase II: Binder-tailings integration

The optimal compositions identified in Phase I, SS at a 7:3 ratio and ST at a 7:3 ratio were then used as the baseline binder formulations for Phase II, in which gold tailings were incorporated to evaluate the mechanical performance of binder–tailings combinations. Table 7 presents compressive strength data for tailings-integrated specimens. STG (cement–tailings) at 5:5 achieved 129.4 kg/cm², while SSTG (cement–subsoil–tailings) at 7:3 reached 77.4 kg/cm². STG exceeded Grade I requirements; SSTG satisfied Grade II (min. 70 kg/cm²), demonstrating structural feasibility.

It is important to note that although the SSTG 6:4 composition reached 67.6 kg/cm², this was below the Grade II minimum and therefore could not be selected, even though it would have reduced cement consumption. The SSTG 7:3 composition (77.4 kg/cm²) was chosen instead because it met the Grade II standard while maintaining moderate cement usage. Similarly, although the SS 6:4 composition in Phase I achieved 94 kg/cm² (close to the Grade I requirement), it was not selected because the SS 7:3 mixture reached 109.3 kg/cm² while using less cement, thereby offering both compliance and cost efficiency.

In the second testing phase (Figure 3), all specimens successfully formed solid matrices without structural failure and underwent compressive strength testing. STG specimens exhibited higher

(a) Portland Cement: Volcanic tuff soil (ST)



(b) Portland Cement: Subsoil (SS)

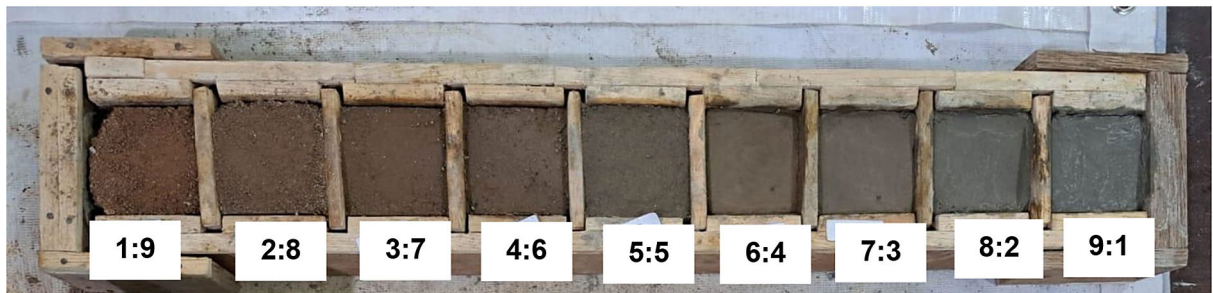


Figure 1. Test specimen with dimensions of $5 \times 5 \times 5$ cm (a) ST mixture, and (b) SS mixture

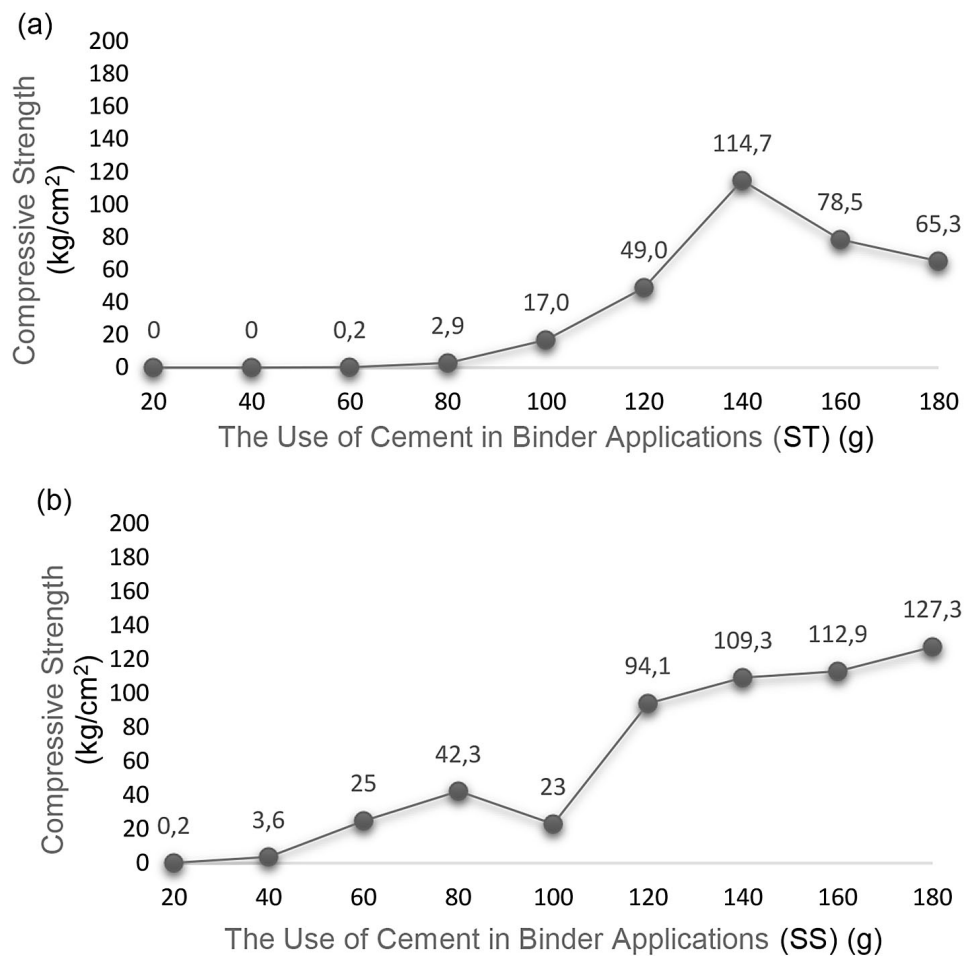


Figure 2. Comparison of compressive strength using cement test specimens (a) ST mixture (b) SS mixture with dimensions of $5 \times 5 \times 5$ cm

Table 7. Compressive strength test results of phase II specimens with dimensions of $5 \times 5 \times 5$ cm after 28 days of drying process

Composition variations	Compressive strength value (kg/cm ²)		
	SSTG	STTG	STG
1:9	0.4	0.8	1.1
2:8	1.5	0.9	5.5
3:7	2.1	3.8	10.6
4:6	8.2	14.2	52.8
5:5	17.3	21.9	129.4
6:4	67.6	57.4	124.7
7:3	77.4	83.8	134.2
8:2	64.9	79.6	153.4
9:1	66.7	74.2	132.8

compressive strength than SSTG and STTG, attributed to their higher silica content. The silica promotes the formation of calcium silicate hydrate (C-S-H), enhancing matrix bonding and densification, which improves mechanical performance [35,36]. However, excessive silica may reduce strength by forming less effective binders due to

imbalanced reactions with calcium hydroxide. Additional binders can increase calcium oxide content, potentially worsening this effect. Therefore, optimal silica content is essential to achieve maximum compressive strength in concrete.

The final selection of optimal compositions for Phase II was based on achieving maximum

(a) Cement + Tanah Tras : Tailing (STTG)**(b) Cement + Subsoil : Tailing****(c) Cement : Tailing (STG)****Figure 3.** Comparison of compressive strength with cement usage in test specimens (a) STTG (b) SSTG (c) STG with dimensions of $5 \times 5 \times 5$ cm

compressive strength while minimizing cement usage, as illustrated in Figure 4. The SSTG 7:3 mixture achieved 77.4 kg/cm², meeting the SNI 03-0349-1989 requirement for Grade II concrete blocks. The STG 5:5 mixture reached 129.4 kg/cm², exceeding the Grade I standard. Both mixtures demonstrated effective mechanical performance with efficient cement use, underscoring their economic and structural advantages. These

outcomes support sustainable construction practices by ensuring resource efficiency without compromising quality.

Full-size concrete blocks

To validate the laboratory-scale findings, full-size concrete blocks (40 × 20 × 10 cm) were produced using the optimal Phase II formulations – STG (5:5) and SSTG (7:3). The compressive

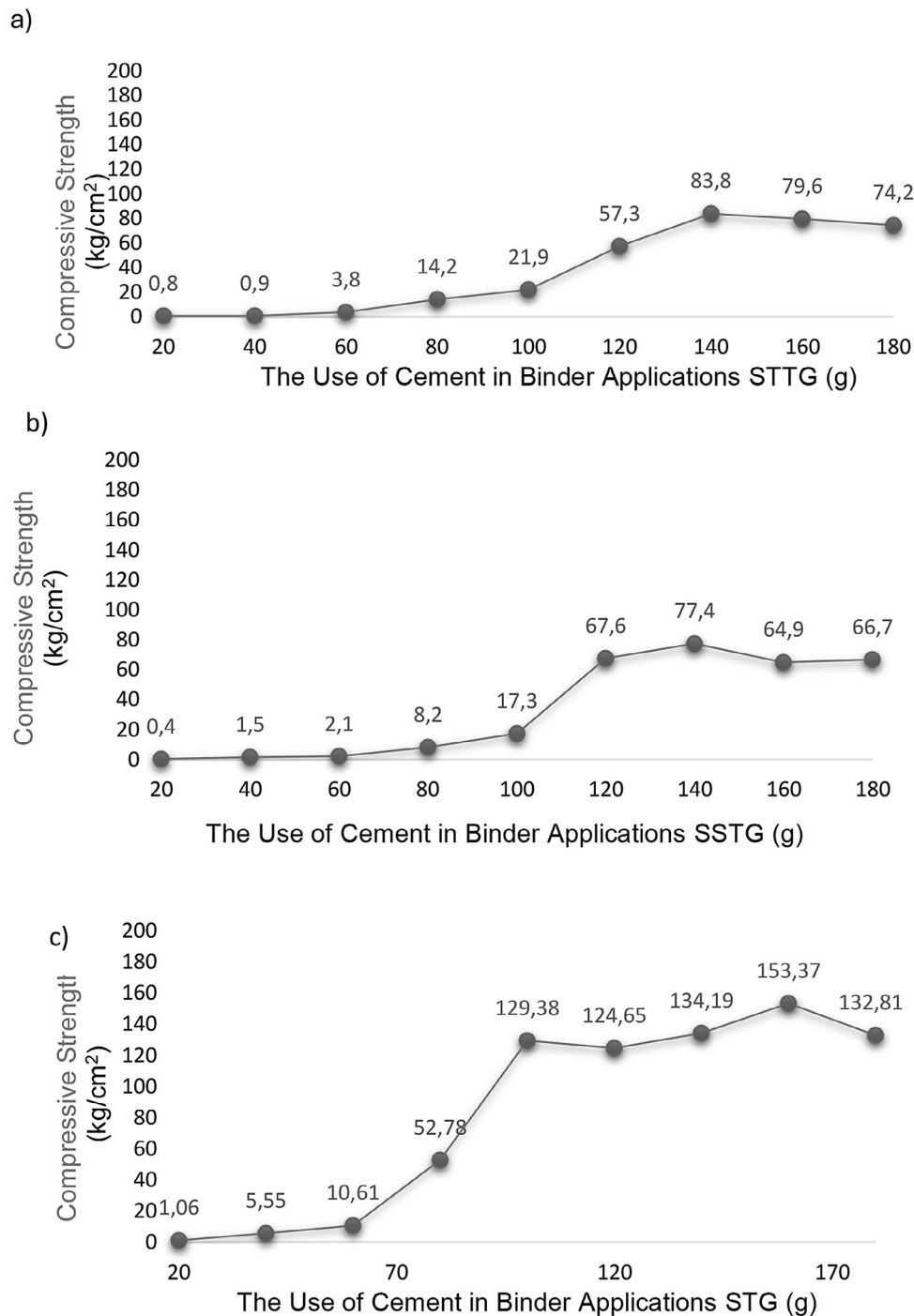


Figure 4. Comparison of compressive strength using cement test specimens (a) STTG (b) SSTG (c) STG with dimensions of 5 × 5 × 5 cm

strengths of these blocks were 102.33 kg/cm² for STG and 68.32 kg/cm² for SSTG. While the STG blocks met the Grade I standard, the SSTG blocks were slightly below the Grade II threshold; however, they still exhibited structural integrity and met durability requirements in terms of water absorption, which was 17.36% for STG and 15.75% for SSTG [37]. The detailed results of compressive strength and water absorption tests are provided in Table 8.

Environmental safety

TCLP leachability test

The leachability of hazardous contaminants was evaluated using the toxicity characteristic leaching procedure (TCLP) following the U.S. EPA Method 1311, which is also referenced in the Indonesian National Standard (SNI 03-3240-1994). In this procedure, ground concrete block samples (40 × 20 × 10 cm) were agitated with an acetic acid buffer solution at a liquid-to-solid ratio of 20:1 for 18 ± 2 hours. The resulting leachate was then filtered and analyzed using Inductively coupled plasma-optical emission spectroscopy (ICP-OES) for metals and atomic absorption spectroscopy (AAS) for mercury. This method detects the potential release of toxic metals under simulated landfill conditions. One limitation of the TCLP method is that it may not fully replicate field leaching behavior over long-term exposure, but it is widely recognized for regulatory compliance and comparative assessment. TCLP results in Table 9, confirmed that all heavy metal concentrations from STG and SSTG blocks were below national limits. No hazardous leaching was observed, confirming environmental safety [38].

Economic feasibility analysis

The SSTG 7:3 mixture offers a balance between mechanical strength and material efficiency. Although STG 5:5 provides higher strength, SSTG reduces cement use, enhancing

cost-effectiveness. This supports circular economy strategies through the repurposing of mining waste [39]. To provide a quantitative comparison, Table 10 presents the estimated material cost per cubic meter of concrete blocks for each optimal mixture. Cement prices were based on the average local market value in 2025 (IDR 60,000 per 50 kg), and tailings/subsoil were considered cost-free as waste materials, with only processing costs included. These calculations indicate that SSTG 7:3 offers approximately 18% lower production cost compared to STG 5:5, while still meeting the Grade II strength requirement.

DISCUSSION

Mechanical performance enhancement

The integration of gold mining tailings into concrete mixtures significantly improved compressive strength, particularly in the 5:5 cement-tailings blend, which achieved 102.33 kg/cm². This surpasses the minimum requirement for Grade I concrete blocks, indicating the efficacy of tailings as a supplementary cementitious material. The high silicon dioxide (SiO₂) content in the tailings likely facilitated pozzolanic reactions, forming additional calcium silicate hydrate (C-S-H) phases that enhance matrix density and strength. This observation aligns with findings by Nadir and Ahmed, who reported strength improvements in concrete incorporating pozzolanic materials [37]. The 7:3 cement-subsoil-tailings mixture, while exhibiting a lower compressive strength of 68.32 kg/cm², still met Grade II standards. The balanced composition of aluminum oxide (Al₂O₃) and silicon dioxide in the subsoil contributed to effective particle packing and binding, enhancing mechanical integrity. These results demonstrate the potential for optimizing binder compositions to balance strength and material efficiency. (Al₂O₃) and silicon dioxide provided effective particle packing and additional binding, contributing to mechanical integrity. These results highlight the balance between maximizing

Table 8. Comparison of compressive strength for cement-tailings and cement-subsoil-tailings mixtures

Block type	Average compressive strength (kg/cm ²)	Standard deviation	Water absorption (%)
Blocks STG ¹	102.33	9.84	17.36
Blocks SSTG ²	68.32	14.35	15.75

Note: ¹ STG concrete block with a 5:5 composition and dimensions of 40 × 20 × 10 cm, ² SSTG concrete block with a 7:3 composition and dimensions of 40 × 20 × 10 cm.

Table 9. Leachability results of hazardous contaminants in cement-tailings and cement-subsoil-tailings blocks

No.	Pollutant.	Test results (mg/L)**		Nasional standard quality (mg/L)
		STG concrete block (5:5 composition)	SSTG concrete block (7:3 composition)	
1	Antimony	0.20	0.13	1.00
2	Arsenic	0.00	0.00	0.50
3	Barium	0.37	0.31	35.00
4	Beryllium	0.00	0.00	0.50
5	Boron	0.00	0.00	25.00
6	Cadmium	0.00	0.00	0.15
7	Hexavalent chromium	1.30	0.00	2.50
8	Copper	0.00	0.00	10.00
9	Lead	0.00	0.00	0.50
10	Mercury	0.00	0.00	0.05
11	Molybdenum	0.05	0.07	3.50
12	Nickel	0.00	0.00	3.50
13	Selenium	0.00	0.00	0.50
14	Silver	0.00	0.00	5.00
15	Tributyltin oxide	tt*	tt*	0.05
16	Zinc	0.00	0.00	50.00

Note: * tt – not detected, ** the testing was conducted on concrete blocks with dimensions of 40 × 20 × 10 cm that had been ground/smoothed.

Table 10. Estimated material cost per cubic meter of optimal mixtures

Mixture type	Cement content (kg/m ³)	Cement cost (IDR)	Processing cost of tailings/subsoil (IDR)	Total estimated cost (IDR)
STG 5:5	350	420,000	50,000	470,000
SSTG 7:3	280	336,000	50,000	386,000

compressive strength and minimizing binder usage, offering a cost-effective solution without compromising performance (Figure 5).

Durability and environmental performance

Water absorption tests revealed that cement-tailings blocks absorbed 17.36% water, while cement-subsoil-tailings blocks absorbed 15.75%. These values fall within acceptable ranges, suggesting adequate durability and resistance to moisture ingress. The denser microstructure resulting from pozzolanic reactions likely contributed to reduced porosity and enhanced durability. Environmental safety assessments using the toxicity characteristic leaching procedure (TCLP) indicated that all concrete specimens had leachate concentrations well below regulatory limits. This confirms the effectiveness of the solidification process in immobilizing hazardous contaminants, aligning with previous

research demonstrating the environmental safety of waste-based construction materials [38].

Comparison with previous studies

The findings of this study are in agreement with prior research emphasizing the feasibility of incorporating industrial waste into construction materials. For instance, mining by-products have been shown to be repurposed into structurally sound materials, resulting in cost reductions and decreased environmental impact [40]. Similarly, the current study demonstrates that, when appropriately processed and blended, gold mining tailings can produce concrete blocks that meet structural and environmental standards. In comparison with waste-based concretes utilizing materials such as fly ash and slag, the mechanical performance of the cement-tailings mixture in this study remains competitive. The compressive strength results are consistent with those

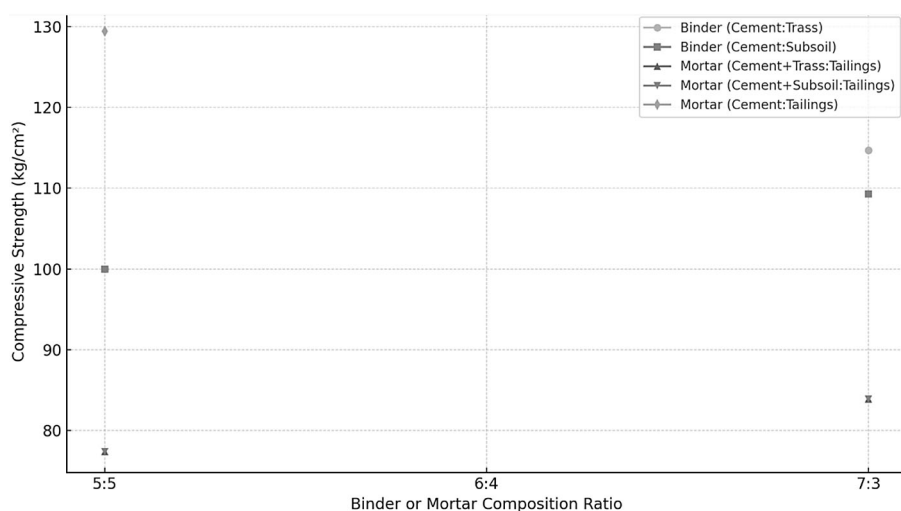


Figure 5. Further illustrates the comparative compressive strengths of different binder ratios, emphasizing the mechanical advantage of optimized mixtures

reported in fly ash-modified concretes, affirming the structural viability of mining tailings as a sustainable alternative [41].

Economic and practical implications

The utilization of gold mining tailings in concrete production offers economic benefits by reducing the reliance on conventional raw materials and minimizing waste disposal costs. The 7:3 cement-subsoil-tailings mixture, in particular, presents a cost-effective alternative due to reduced cement consumption while maintaining adequate compressive strength. This approach supports sustainable construction practices and aligns with circular economy principles by repurposing industrial waste into valuable construction materials.

Practical and environmental implications

The successful incorporation of gold mining tailings into concrete blocks presents significant practical and environmental benefits. On a practical level, this approach reduces reliance on traditional raw materials, addressing supply constraints in the construction industry. Environmentally, this strategy mitigates the harmful effects of mining waste disposal, such as soil and water contamination, while lowering greenhouse gas emissions associated with cement production.

Moreover, this study provides evidence supporting the scalability of solidification methods for hazardous waste management. Implementing this technology in mining regions could help local

communities manage waste sustainably while fostering economic development through the production of affordable construction materials.

Limitations of the study

While the study demonstrates promising results, it is limited to laboratory-scale experiments under controlled conditions. Field studies are necessary to assess the long-term performance of these materials under varying environmental conditions, such as temperature fluctuations and exposure to aggressive agents. Additionally, further research should explore the incorporation of other supplementary materials and the optimization of curing processes to enhance the mechanical and durability properties of the concrete blocks.

CONCLUSIONS

This study demonstrates that incorporating detoxified gold mining tailings into concrete block production via solidification/stabilization can yield high-performance, environmentally safe materials. The 1:1 cement–tailings formulation achieved 102.33 kg/cm² (Grade I), and the 7:3 cement–subsoil–tailings blend reached 68.32 kg/cm² (Grade II), with both mixtures meeting water absorption and TCLP leaching criteria. However, laboratory conditions and limited batch sizes constrain the assessment of long-term durability under field environments and variable climatic exposures. Future investigations should evaluate aging behaviour,

freeze-thaw resistance, and real-scale block production, as well as explore alternative SCMs and curing regimes. Scaling up these findings will clarify the economic viability and carbon-reduction potential of repurposing mining waste for sustainable construction on an industrial level

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