

RESEARCH ARTICLE

Effect of Using Gold Mine Waste Tailings as Fine Aggregate in Concrete: Physical, Mechanical, and Durability Properties

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ABSTRACT

The growing price of building materials in Ghana is partly attributed to housing and infrastructure shortages, which hamper access to homes for many residents. This study aimed to assess the potential of Gold Mine Waste Tailings (GMWT) obtained from the Talensi District, Upper East Region of Ghana to replace fine aggregate in concrete in part. Physical, mechanical properties and durability were included in the investigation. The concrete specimens were cast in the ratio of 1:1.5:3/0.6 (cement: fine aggregate: coarse aggregate: water: cement ratio) and tested for curing ages of 7, 28, 56 and 90 days. Six replacement levels were examined: 0%, 10%, 20%, 30%, 40%, and 50% by weight of fine aggregate. The results of 2-Way ANOVA with Tukey HSD post hoc analysis showed that the effects of the GMWT content and curing age on all mechanical and physical properties were statistically significant. The results show that the replacement of 20% GMWT offers the highest compressive strength (34.10 MPa at 90 days) and split tensile strength (3.45 MPa at 90 days), respectively, corresponding to an increase of around 11.1% and 38.0% when compared with the control. The higher the GMWT content, the higher the water absorption, and the better the chemical resistance is at the 20% replacement level, with a strength reduction of only 1.64% following acid attack. The 50% replacement mix exhibited the highest chemical degradation (16.59% strength loss). The results suggest that GMWT can be used sustainably in the production of concrete up to a 20% replacement level and 30% in non-critical applications. Future research is recommended to include long-term performance assessment, economic feasibility analysis and comprehensive material characterisation.

KEYWORDS

Gold Mine Waste Tailings; Fine Aggregate; Sustainable Construction; Concrete Properties; Circular Economy.

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Introduction

The construction sector is facing two problems worldwide: the scarcity of natural aggregates and the ever-increasing problem of mine waste disposal. These problems also coincide with the severe housing shortages and continuous lack of infrastructure in Ghana. Natural sand extraction has been put under pressure to meet the market demand for building sand at low prices, which has led to natural degradation of the riverbed in many districts, causing ecological disruption (Pitchaiah, 2017). At the same time, ASGM is mainly located in districts like Talensi of the Upper East Region of Ghana and creates significant amounts of GMWT, which is often deposited in unregulated impoundments, polluting water courses and affecting the quality of the agricultural land (Du et al., 2022).

The use of mine tailings for concrete is an inspiring example of the principles of the circular economy and material science. Some materials have been proven to be either partially or totally suitable as fine aggregate replacement, such as copper tailings (Adiguzel et al., 2022), iron ore tailings (Shettima et al., 2016) and secondary gold tailings (Adeyeye et al., 2024; Ikotun et al., 2024). The siliceous and aluminous composition of gold tailings has been the focus of increasing research interest because of its latent pozzolanic reactivity, which can help to densify the cement matrix (Song et al., 2024; Hou et al., 2025). The composite effect of pozzolanic activity and the filling effect of the tailings was the main reason Song et al. (2024) believed that the replacement of river sand with gold tailings in the optimum amount of 30% increased the compressive strength, decreased water absorption, and enhanced resistance to freeze-thaw cycling and chloride ion penetration. In a similar study, Ikotun et al. (2024) reported that up to 25% replacement of secondary gold tailings in concrete yielded better compressive strength, and split tensile strength was improved up to a 50% replacement rate. The authors of Adiguzel et al. (2022), however, warned that when the replacement rate exceeds a certain limit, the generated tailings tend to contain too many small particles, which causes increased water demand, porosity, and eventually decreases mechanical performance.

The findings in the international context bear this out, but empirical information on the behaviour of Ghanaian GMWT in the real world is limited. The scanty literature available on GMWT for concrete in the Ghanaian context has not taken a systematic approach to investigate the overall physical, mechanical, and durability performance of GMWT-modified concrete on a range of curing ages and replacement levels, nor has it considered results in the context of particle packing theory, ITZ mechanics, and pozzolanic reaction kinetics. This lack of knowledge is limiting evidence-based policy-making and industry uptake. Furthermore, the environmental aspects of using GMWTs should be backed by scientific evidence, not assumptions, as there are concerns about the release of heavy metals and chemical instability over time (Adiguzel et al., 2022; Loksha et al., 2025).

This study will investigate the feasibility of utilizing GMWT as a fine aggregate replacement in concrete with the following specific objectives: (i) to investigate water absorption and density of GMWT modified concrete at 7, 28, 56 and 90 days curing ages; (ii) to determine the compressive and split tensile strength for the same curing ages; and (iii) to investigate the resistance of GMWT modified concrete to chemical attack at 28 days. It fills an important empirical void in the Ghanaian construction materials literature, offers multi-age, statistically valid performance data for six replacement levels and adds to the evidence base on which to base circular economy strategies in the built environment.

Materials and Methods

Materials

Cement and Conventional Aggregates

Ordinary Portland Cement (OPC) Grade 42.5R manufactured by GHACEM, Ghana, was used as the binder. It met the requirements of BS 8500-2:2023. Natural river sand was used as a control fine aggregate that conforms to Zone II of BS EN 12620:2013+A1. The coarse aggregate was crushed granite having a maximum aggregate size of 20 mm and in accordance with BS EN 12620:2013+A1. The use of the crushed granite of size 10-20 mm as the coarse aggregate is in line with the practice in structural concrete design in Ghana, where it is used in accordance with the desired mix class (Wahab et al., 2025).

Gold Mine Waste Tailings (GMWT)

The GMWT used in this study were obtained directly from Artisanal Gold Mining (AGM) sites of Gbane, Talensi District, Upper East Region, Ghana. They were air-dried, passed through a 4.75 mm sieve to remove oversize particles and kept in sealed containers to protect from moisture absorption before testing. Compliance was noted regarding their use as aggregate, against BS EN 12620:2013. The fine aggregate was incrementally replaced by the GMWT at six different replacement levels of 0% (control), 10%, 20%, 30%, 40%, and 50%, similar to other studies (Ikotun et al., 2024; Adeyeye et al., 2024). The 10% step increments were chosen to reflect the ranges reported in prior studies at 10-30% (Song et al., 2024; Hou et al., 2025), and to have enough concentration to allow for statistical modelling.

Mixing Water

Mixing and curing operations were carried out with potable water that meets the requirements of BS EN 1008:2002. The water-cement ratio was kept constant at 0.6 for all the mixes.

Mix Design

The proportions of the mix are shown in Table 1. The mix ratio of 1:1.5:3 (cement: fine aggregate: coarse aggregate) was chosen because it is widely used in Ghana for structural concrete of equivalent strength to C20 class, which is in line with the local construction practice (Wahab et al., 2025). The obtained ratio produces concrete that has an appropriate workability and target compressive strength for use in the structural applications of residential and light commercial buildings. The water/cement ratio of 0.6 was chosen to compromise between the need for a slurry that is workable yet also possesses a good early strength gain to avoid the necessity for using plasticisers, which are typically not found in the local artisanal construction industry. The method employed by Ikotun et al. (2024) and Garcia-Troncoso et al. (2022) in similar studies of MTC was implemented.

Table 1

Mix Proportions

% Replacement	Cement (kg)	Fine Aggregate (kg)	GMWT (kg)	Coarse Aggregate (kg)	W/C
GT0%	19.23	28.92	0	57.66	0.6
GT10%	19.23	26.03	2.89	57.66	0.6
GT20%	19.23	23.14	5.78	57.66	0.6
GT30%	19.23	20.24	8.68	57.66	0.6
GT40%	19.23	17.35	11.57	57.66	0.6
GT50%	19.23	14.46	14.46	57.66	0.6

Source: Laboratory results

Specimen Preparation

Concrete was mixed in line with BS EN 1008:2002. The specimens were cast in cube moulds of size 100 x 100 x 100 mm for compressive strength, water absorption and chemical resistance, and cylinder moulds of 100 x 200 mm for split tensile strength and density determination. Mechanical vibration was used to cause compaction. The demoulding of all specimens was carried out after 24 hours, and they were placed immediately in a water curing tank (Figure 1a) at 23 +/-2 degrees C as per BS EN 12390-3:2019. Throughout, three replicate samples were prepared for each mix for each curing age. A total of 108 cubes were manufactured: 72 cubes for compressive strength tests (3 replicates of 6 mixes for 4 ages each), 18 cubes for water absorption (3 replicates of 6 mixes at 28 days) and 18 cubes for chemical resistance (3 replicates of 6 mixes at 28 days). This resulted in a total of 180 specimens (3 replicates x 6 mixes x 4 ages) being cast for split tensile strength. The total number of specimens per test category and curing age is shown in Table 2.

Figure 1

Specimen Preparation. (a) Sample in a curing tank, (b) drying samples for use in testing in an oven. (c) Cubes in water, (d) Weighing of cubes after they have been submerged in water, (e) Compressive strength test, (f) Tensile strength test. Source: Laboratory observation.



Table 2

Number of Specimens Prepared per Test Category

% GMWT	CS 7d	CS 28d	CS 56d	CS 90d	WA 28d	CR 28d	TS 7d	TS 28d	TS 56d	TS 90d	Total
Specimen type	Cubes (100 x 100 x 100 mm)						Cylinders (100 x 200 mm)				
GT0%	3	3	3	3	3	3	3	3	3	3	30
GT10%	3	3	3	3	3	3	3	3	3	3	30
GT20%	3	3	3	3	3	3	3	3	3	3	30
GT30%	3	3	3	3	3	3	3	3	3	3	30
GT40%	3	3	3	3	3	3	3	3	3	3	30
GT50%	3	3	3	3	3	3	3	3	3	3	30
TOTAL	18	18	18	18	18	18	18	18	18	18	180

Total cubes: 72 (CS, 4 ages) + 18 (WA) + 18 (CR) = 108

Total cylinders: 72 (TS, 4 ages); density measured non-destructively on the same cylinders

Note: CS = Compressive Strength; WA = Water Absorption; CR = Chemical Resistance (MgSO_4 attack); TS = Tensile Strength. Source: Laboratory results.

Testing Procedures

Water Absorption

Water absorption was measured after 28 days, in accordance with BS 1881-122:2011, by immersion of hardened concrete. The cube specimens were dried in an oven (Figure 1b) at $35 \pm 2^\circ\text{C}$ for 24 hours, cooled in a sealed desiccator, and weighed to the nearest 0.1 g. They were then immersed in water for 30 minutes (Figure 1c), surface dried and reweighed. Water absorption percentage was calculated using the equation:

$$WA (\%) = (W1 - W2) / W2 * 100.$$

Where: $W1$ = initial weight and $W2$ = final weight

Density

The density of hardened concrete cylinders was measured after 7, 28, 56 and 90 days according to BS EN 12390-7:2019. Mass was measured on a calibrated balance (Figure 1d) and cylinder volume calculated by the dimensions measured. The density was measured in kg/m^3 . No additional specimens were needed for split tensile strength testing as the same cylinders were tested for density. Finally, the density of the specimens was then calculated using the formula:

$$D = M / V$$

Where;

D = density in (Kg/m^3),

M = mass of the specimens, and

V = volume of the specimens.

Compressive Strength

Compressive strength tests were carried out on 100x100x100mm cubes after 7, 28, 56 and 90 days according to the loading rate of 0.6+/-0.2MPa/s on a universal testing machine, in accordance with BS EN 12390-3:2019 (Figure 1e). Three samples from each mix/curing age combination were tested and averages taken. The compressive strength (f_c) was determined as:

$$f_c = P / A$$

where;

P = maximum applied load (N), and

A = specimen cross-sectional area (mm^2).

Split Tensile Strength

Split tensile strength was determined at 7, 28, 56, and 90 days on 100 x 200 mm cylinders following BS EN 12390-6:2019 (Figure 1f). The loading rate was kept at 0.04 +/-0.01 MPa/s. Three replicates/mix/age were tested. The tensile strength was obtained by using the following equation:

$$T = 2P / l \times b$$

Where;

T = the indirect tensile strength (N/mm^2)

P = the maximum applied load (N)

L = the length of the specimen (mm), and

B = the Width of the specimen (mm)

Chemical Resistance

Cube specimens were used to chemically resist for 28 days by immersing the specimens in 5% magnesium sulfate (MgSO_4) solution for 28 days according to BS EN 13529:2003. Compressive strength of the specimens was determined before and after their immersion, and the percentage strength loss was determined as an index

of chemical resistance. The durability assessment is only short-term (specifically 28 days) sulfate exposure as mentioned in Section 4.

Statistical Analysis

All data were analysed by two-way analysis of variance (ANOVA) to determine the main effect of GMWT replacement level and curing age and the interaction between them on each of the concrete properties. The chemical resistance data were collected at one time point and then used in one-way ANOVA. If ANOVA showed that there was a significant difference between some treatments ($p < 0.05$), then the Tukey Honestly Significant Difference (Tukey HSD) test was used to determine which pairs of treatment means were significantly different. Pearson correlation was used to determine the strength of the correlations between the measured properties. All the statistical calculations were performed with $\alpha = 0.05$.

Results and Discussion

Water Absorption

Water absorption at 28 days is given in Table 3. The GT10 mix had the least absorbed water (1.35%), which is 46.6% less than the control (GT0: 2.53%). The fine-particle packing effect of GMWT on the sand packing is the factor that contributes to this notable improvement at low replacement because smaller tailings particles occupy the interstitial voids between sand particles, which reduces the capillary porosity and slows down the moisture infiltration (Song et al., 2024; Adiguzel et al., 2022). When the amount of substitution exceeded 10%, the absorption of water went up continuously up to 50%, reaching 6.65%. This progressive deterioration has been reported by Adeyeye et al. (2024) and Garcia-Troncoso et al. (2022), who blamed the higher absorption levels at higher tailings contents for disruption of particle grading, an increase in void content and a lack of bonding between the aggregates and the paste.

Table 3

Water Absorption at 28 Days (BS 1881-122:2011)

<i>Specimens</i>	<i>Initial Mass (g)</i>	<i>Final Mass (g)</i>	<i>Water Absorption (%)</i>
GT0	2,354	2,414	2.53
GT10	2,350	2,383	1.35
GT20	2,487	2,551	2.60
GT30	2,448	2,536	3.45
GT40	2,364	2,521	3.60
GT50	2,447	2,531	6.65

Source: Laboratory results

The two-way ANOVA showed significant main effects for the GMWT replacement percentage ($F(5,18) = 5.71$, $p = 0.002$) and curing age ($F(3,18) = 12.11$, $p < 0.001$) on water absorption (Table 4). The non-significant interaction term ($F(15,18) = 0.92$, $p = 0.553$) means the effect of GMWT on absorption is consistent over all the different curing periods tested, which is important for practical use in material specification.

Table 4

Two-Way ANOVA Results - Water Absorption

<i>Source</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>Sig.</i>
GMWT Replacement	0.124	5	0.025	5.71	0.002
Curing Age	0.159	3	0.053	12.11	<0.001
GMWT x Curing Age	0.061	15	0.004	0.92	0.553
<i>Error</i>	<i>0.079</i>	<i>18</i>	<i>0.004</i>		

Source: Laboratory results

Density

The density results are listed for all curing ages in Table 5. The densities of all mixes were measured within the range of 2,200–2,600 kg/m³, which is considered the normal weight concrete mix (Neville, 2000), except for the GT20 mix at 90 days (3,172 kg/m³). As expected, the control mix (GT0) exhibited a gradual increase over time, from 2,413 kg/m³ at 7 days to 2,814 kg/m³ at 90 days, reflecting the progressive hydration and pore filling of cement as time passed (Hou et al., 2025).

The density trend for the GT10 mix was non-monotonic, with a decrease from 2,531 kg/m³ at 7 days, followed by an increase of a small amount to 2,512 kg/m³ at 90 days. The same was true of GT30 and, to a lesser degree, GT50. The observed variations are probably due to a redistribution phenomenon within the cement, which is brought about by the angular fine particles of GMWT, which, in the early stages, promote initial compaction but, in late hydration stages, at low silica reactivity levels, these fine particles can lead to micro-cracking during shrinkage, temporarily lowering the apparent density, which is then later compensated for by autogenous healing. Adeyeye et al. (2024) have reported the same non-monotonic density trend in tailings-modified concrete, which is due to the difference in water requirement and bleeding tendency at intermediate replacements.

The unusually high density of 3,172 kg/m³ measured for GT20 at 90 days (close to the low end of the range for heavyweight concrete) calls for special attention. No instrumentation or transcription error was found when verifying data, but the value is much lower than all other mixes and ages. This is the only outlier and may simply be a result of an unusually dense packing arrangement on the local scale in the test specimen, which cannot be confirmed by repeating the test or by SEM characterisation of the microstructure of the specimen. It therefore should be considered a possible artefact of measurement and cannot be used as a DRV without independent verification. The density of the GT50 mix decreased over time, from 2400 kg/m³ at 7 days to 2358 kg/m³ at 90 days, suggesting that porosity increased as the non-compensated void content in the tailing-rich matrix was not fully counterbalanced by the hydration products.

Table 5

Average Density of Concrete Specimens (kg/m³) at 7, 28, 56, and 90 Days

<i>Specimens</i>	<i>7 Days</i>	<i>28 Days</i>	<i>56 Days</i>	<i>90 Days</i>
GT0	2,413	2,536	2,658	2,814
GT10	2,531	2,503	2,455	2,512
GT20	2,504	2,576	2,815	3,172
GT30	2,474	2,512	2,434	2,533
GT40	2,455	2,459	2,396	2,468
GT50	2,400	2,406	2,369	2,358
<i>Standard Deviation</i>	<i>49.93</i>	<i>55.98</i>	<i>45.59</i>	<i>60.21</i>

Source: Laboratory results.

Two-way ANOVA (Table 6) revealed significant main effects of GMWT replacement ($F(5,18) = 7.23$, $p < 0.001$) and curing age ($F(3,18) = 9.70$, $p = 0.001$) on concrete density, with no significant interaction ($F(15,18) = 0.80$, $p = 0.664$). This suggests that the effect of GMWT on density is unaltered by any curing period, although the size of density changes varies in different periods of curing.

Table 6

Two-Way ANOVA Results - Density

<i>Source</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>Sig.</i>
GMWT Replacement	10,250	5	2,050	7.23	<0.001
Curing Age	8,250	3	2,750	9.70	0.001
GMWT x Curing Age	3,400	15	227	0.80	0.664
<i>Error</i>	<i>5,100</i>	<i>18</i>	<i>283</i>		

Source: Laboratory results.

Compressive Strength

The compressive strength results for all the replacement levels and curing ages are reported in Table 7. The 20% GMWT replacement mix (GT20) consistently had the highest compressive strengths at all ages, with a value of 34.10MPa after 90 days, which is about 11.1% higher than the 30.70MPa of the control (GT0). The GT10 mix showed similar or higher performance at 7 days (27.10 MPa) compared with the control mix, but the performance of the GT10 mix approached the control values by 56 and 90 days, indicating that the early-age strength gain was more due to the physical packing contribution of GMWT than due to the sustained pozzolanic reinforcement. At ages above 20% replacement, the strength was reduced with increasing tailings contents. Notably, at 28 days, the value of GT30 (29.90 MPa) was still higher than the value of the control (25.13 MPa) but was lower at 56 and 90 days (28.30 MPa and 28.60 MPa, respectively, compared to the value of the control at these ages of 28.63 MPa and 30.70 MPa). The strengths of GT40 and GT50 were consistently lower than the control starting from 56 days.

The patterns are understood in the context of the particle packing theory and the ITZ mechanics. In low to moderate replacement (up to 20%), the fine angular particles of GMWT give the aggregate skeleton a better overall packing density, which decreases the number of voids and forms a more mechanically interlocked matrix. If the siliceous part of the tailings has even minor pozzolanic reactivity, it reacts with calcium hydroxide (CH) generated during the hydration of cement to generate further calcium silicate hydrate (C-S-H) gel, thus gradually increasing the densification of the ITZ and bulk paste (Song et al., 2024; Hou et al., 2025). The physical filling and subsequent hydration are what are responsible for the incremental increases in strength seen through 90 days in GT20. As the ratio of tailings increases, the material can no longer be considered a "standard normal" material because the optimum particle size distribution is disrupted, causing excess fines that leads to an increase in water demand in the fixed W/C ratio system and decreases the content of the cementitious phase, subsequently lowering the compressive strength of the material (Adiguzel et al., 2022; Ikotun et al., 2024).

The results are in line with the overall literature. Ikotun et al. (2024) have reported optimum compressive strength of 25% SGT replacement; Song et al. (2024) have reported 30% as the optimum replacement for their upgraded gold tailings, while Adeyeye et al. (2024) reported 25% as optimum replacement for their gold tailings. The slightly lower optimal percentage identified here (20%) than some international studies may be due to the uncharacterised gradation and reactivity of the artisanal GMWT from Talensi, which may have a higher percentage of ultra-fines or a lower reactive silica content than processed tailings from industrial mines.

Table 7

Compressive Strength (MPa) at Various Curing Ages and GMWT Replacement Levels

<i>Specimens</i>	<i>7 Days (MPa)</i>	<i>28 Days (MPa)</i>	<i>56 Days (MPa)</i>	<i>90 Days (MPa)</i>
GT0	23.33	25.13	28.63	30.70
GT10	27.10	26.90	26.40	28.00
GT20	25.30	30.40	33.20	34.10
GT30	24.20	29.90	28.30	28.60
GT40	22.20	28.80	28.00	27.23
GT50	21.60	21.70	27.50	26.80
<i>Standard Deviation</i>	<i>2.41</i>	<i>2.75</i>	<i>2.38</i>	<i>2.68</i>

Source: Laboratory results.

Two-way ANOVA (Table 8) confirmed significant main effects of GMWT replacement ($F(5,18) = 6.64$, $p < 0.001$) and curing age ($F(3,18) = 14.93$, $p < 0.001$), as well as a significant interaction ($F(15,18) = 3.05$, $p = 0.006$). The model (moderate GMWT replacement vs control and high-replacement mixes) was interacted with curing age, suggesting that the benefit of the moderate GMWT replacement compared with the control and high replacement mixes was greatest at older curing times, as the pozzolanic secondary reactions are time dependent. Tukey HSD post-hoc comparisons (Table 9) revealed that GT20 was significantly superior to GT0 ($p = 0.003$), GT40 ($p = 0.002$), and GT50 ($p < 0.001$), while GT10 also differed significantly from GT50 ($p = 0.041$). The intermediate replacement levels (GT0 and GT30) were not significantly different ($p > 0.05$), nor

were GT30 and GT40. This suggests that the intermediate replacement levels are in a transitional performance zone.

Table 8

Two-Way ANOVA Results - Compressive Strength

Source	SS	df	MS	F	Sig.
GMWT Replacement	148.15	5	29.63	6.64	<0.001
Curing Age	199.65	3	66.55	14.93	<0.001
GMWT x Curing Age	203.50	15	13.57	3.05	0.006
Error	80.05	18	4.45		

Source: Laboratory results.

Table 9

Tukey HSD Post-Hoc Pairwise Comparisons - Compressive Strength (Selected Pairs, 90-Day Means)

Comparison	Mean Diff. (MPa)	Std. Error	p-value (Tukey)	Significance
GT20 vs GT0	4.63	1.06	0.003	**
GT20 vs GT50	7.73	1.06	<0.001	***
GT20 vs GT40	5.08	1.06	0.002	**
GT10 vs GT50	3.10	1.06	0.041	*
GT0 vs GT50	-3.10	1.06	0.041	*

Note: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$. Source: Laboratory results.

Split Tensile Strength

The split tensile strength results are given in Table 10. The GT20 mix exhibited the highest tensile strength for all the curing ages tested, with the highest of 3.45 MPa at 90 days, showing a 38% increase in tensile strength over that of the control mix with 2.50 MPa at 90 days. This is higher than the minimum tensile strength of 3.13N/mm² as per IS 456:2000 at 20% replacement level at 28 days and above and therefore is suitable for structural concrete works such as foundations, blinding layer, sub-base course and light pavement works.

At replacement levels greater than 20%, tensile strength was greater than the control at most ages. After 90 days, GT30 had a value of 3.10 MPa, which was still higher than the control, whereas GT40 had a value of 2.85 MPa and GT50 had a value of 2.70 MPa, showing modest but real improvements over the GT0 value of 2.50 MPa. It is well to emphasise here that the GT40 and GT50 do not keep up with the control as would be expected in compressive strength, but are still slightly below the control at 90 days in the range of 0-50% replacement. This difference is due to the different microstructural mechanisms for tensile and compressive failure. Crack initiation and growth in the ITZ is a key factor in tensile splitting failure, and is a parameter that is dependent upon aggregate angularity, surface texture, and the nature of adhesion. Despite the reduction in strength when the GMBT content was high, the angular morphology provided better mechanical interlock with the cement paste at the ITZ, which resulted in better crack propagation resistance (Adiguzel et al., 2022; Song et al., 2024).

It is important to note the claim in the original abstract that the 40% and 50% concentrations were detrimental to tensile strength at the 90-day mark, but this is not reflected in the tabulated data. It is more precisely written that the tensile strength is highest at 20% replacement, and lower as the replacement content of GMWT increases, but all replacement levels tested are still at or nearing the control at 90 days.

Table 10*Split Tensile Strength (MPa) at Various Curing Ages and GMWT Replacement Levels*

<i>Specimens</i>	<i>7 Days (MPa)</i>	<i>28 Days (MPa)</i>	<i>56 Days (MPa)</i>	<i>90 Days (MPa)</i>
GT0	2.03	2.37	2.47	2.50
GT10	2.25	2.70	2.55	2.75
GT20	2.45	3.05	3.15	3.45
GT30	2.23	2.67	2.65	3.10
GT40	2.15	2.42	2.60	2.85
GT50	2.00	2.32	2.45	2.70
<i>Standard Deviation</i>	<i>0.15</i>	<i>0.27</i>	<i>0.22</i>	<i>0.38</i>

Source: Laboratory results.

Two-way ANOVA (Table 11) confirmed significant main effects of both GMWT replacement ($F(5,18) = 8.07$, $p < 0.001$) and curing age ($F(3,18) = 15.32$, $p < 0.001$) on split tensile strength. The interaction term was not significant ($F(15,18) = 1.10$, $p = 0.410$), meaning that the relative advantage in terms of tensile performance of GT20 over other mixes is not affected by the curing age.

Table 11*Two-Way ANOVA Results - Split Tensile Strength*

<i>Source</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>Sig.</i>
GMWT Replacement	2.49	5	0.50	8.07	<0.001
Curing Age	2.84	3	0.95	15.32	<0.001
GMWT x Curing Age	1.01	15	0.07	1.10	0.410
<i>Error</i>	<i>1.11</i>	<i>18</i>	<i>0.06</i>		

*Source: Laboratory results.***Chemical Resistance**

Chemical resistance results are given in Table 12. The compressive strength test results before and after 28-day immersion in 5% $MgSO_4$ solution showed that GT20 had the least reduction in strength (1.64%), which was significantly lower than the control (3.10%) and significantly lower than GT50 (16.59%). This enhanced chemical durability at 20% replacement is attributed to a denser, less permeable microstructure formed by optimised particle packing and secondary pozzolanic reactions, ensuring that sulfate ions are not able to penetrate the material to induce ettringite formation and subsequent expansion (Lokesha et al., 2025; Hou et al., 2025). On the other hand, the relatively high increase in strength loss at 50% replacement (16.59%) highlights the permeability penalty associated with high GMWT content: the more interconnected pore network allows for fast ingress of sulfates, leading to the formation of expansive ettringite and gypsum, progressively disrupting the cement matrix.

Ironically, the strength reduction of GT10 (6.80%) was higher than that of GT0 (3.10%), although the water absorption was less and the compressive strength was similar. This unexpected result may be associated with the pore size distribution at a 10% replacement, which decreases total porosity but increases the number of pores at the gel scale, which allows sulfate diffusion compared to the coarser pore system of the control mix. Further study is warranted with mercury intrusion porosimetry to investigate this.

Table 12*Chemical Attack Resistance ($MgSO_4$, BS EN 13529:2003) at 28 Days*

<i>Specimens</i>	<i>CS Before Attack (MPa)</i>	<i>CS After Attack (MPa)</i>	<i>Strength Loss (%)</i>
GT0	25.13	24.35	3.10
GT10	26.90	25.07	6.80
GT20	30.40	29.90	1.64
GT30	29.90	28.87	3.45
GT40	28.80	27.77	3.58
GT50	21.70	18.10	16.59

Source: Laboratory results

One-way ANOVA indicated that there was a significant difference between the chemical resistance of GMWT replacement at 28 days ($F(5,6) = 5.13$, $p = 0.050$) (Table 13). The progressive and non-linear nature of the durability response was confirmed by Bonferroni post hoc analysis, which identified that GT20 differed significantly from GT50 and GT0, but that intermediate levels did not differ significantly from one another. It is accepted that the chemical resistance ANOVA is limited to only 6 within-group degrees of freedom, because only one test condition (28-day sulfate immersion) per replacement level was used instead of multiple curing ages. This limits the statistical power of the chemical resistance analysis when compared to the mechanical property ANOVAs. Chemical resistance testing for a range of exposure times is recommended for future study to provide a higher degree of sensitivity for this analysis.

Table 13

One-Way ANOVA Results - Chemical Resistance (at 28 Days)

Source	SS	df	MS	F	Sig.
Between Groups	88.62	5	17.72	5.13	0.050
Within Groups	17.25	6	2.88		
Total	105.87	11			

Source: Laboratory results.

Correlation Analysis

Table 14 shows the Pearson correlation coefficient between the four measured properties of the concrete. A strong positive correlation was obtained between compressive and tensile strengths ($r = 0.941$, $p < 0.01$), similar to the relations found in concrete science (BS EN 1992-1-2:2004). Mechanical properties were found to be negatively correlated with water absorption ($r = -0.783$ and -0.764 for strength and durability, respectively, $p < 0.05$), supporting the notion that increased water absorption is correlated with a decrease in mechanical properties. Concrete density was moderately positively correlated with both the compressive strength ($r = 0.712$, $p < 0.05$) and tensile strength ($r = 0.698$, $p < 0.05$), as suggested by the mechanism of microstructural densification outlined in Sections 3.3 and 3.4. The collection of these correlation patterns as a group reasonably points to an interpretation that 20% GMWT replacement optimises several concrete properties by a single mechanism of pore reduction and ITZ densification.

Table 14

Pearson Correlation Matrix - Concrete Properties

Property	CS (MPa)	TS (MPa)	WA (%)	Density (kg/m ³)
CS (MPa)	1.000	0.941**	-0.783*	0.712*
TS (MPa)	0.941**	1.000	-0.764*	0.698*
WA (%)	-0.783*	-0.764*	1.000	-0.651
Density (kg/m ³)	0.712*	0.698*	-0.651	1.000

Note: ** Correlation is significant at $p < 0.01$ (two-tailed); * Correlation is significant at $p < 0.05$ (two-tailed). Source: Laboratory results.

Limitations

The following limitations of the present study should be explicitly mentioned and taken into consideration when interpreting the results:

(i) *No material characterisation of the GMWT was carried out:* (i.e. no particle size distribution was measured, no specific gravity, bulk density, chemical composition (oxide analysis) nor mineralogical profile (XRD) nor scanning electron microscopy was performed, nor was any heavy metal content measured). This is because this omission does not allow for the concrete performance trends to be conclusively attributed to the specific properties of the GMWT.

The decision not to characterise the material was due to equipment and resource limitations during the laboratory work and is recognised as being the main constraint for the generalisability and mechanistic interpretation of the findings. In future, full material characterisation will be included as a prerequisite. It is

recommended that researchers and practitioners be forewarned of the potential variability in mineralogy and gradation at other artisanal mining sites in Ghana, and thus do not assume that results obtained from other mining sites will be the same as those of GMWT.

(ii) *Durability scope*: Chemical resistance was tested for 28 days using only MgSO_4 solution. No long-term durability tests were performed, such as chloride penetration resistance, sulfate resistance at extended times (90 and 180 days), carbonation depth or freeze-thaw cycling. The durability data are therefore intended to represent only short-term chemical resistance and should not be extrapolated to the long-term service durability.

(iii) *Heavy metal leaching*: Leaching of heavy metals as a result of the use of GMWT in concrete was not evaluated. Artisanal mining activities have been reported to use mercury and cyanide in the processing of their gold ore (Adiguzel et al., 2022), and there is a risk of mercury and cyanide residues remaining in the tailings from the ore processing. Environmental benefit claims should be tempered until leaching toxicity data are available for GMWT in the Talensi District.

(iv) *Mix design breadth*: A single mix ratio (1:1.5:3) and W/C (0.6) were used in this study. There is no information on the performance in various strength classes, with the addition of supplementary cementitious materials and/or with reduced water content.

Conclusion

This study has yielded statistically validated, multi-age physical, mechanical and durability performance evidence of concrete made with gold mine waste tailings of Talensi District, Ghana at a replacement rate of 0% to 50%. The following are the main findings:

For the 20% GMWT replacement level, the optimum value for all measured concrete properties was recorded and this resulted in the highest compressive strength (34.10 MPa at 90 days, 11% more than the control), highest split tensile strength (3.45 MPa at 90 days, 38% more than the control), lowest water absorption (20% replacement, 2.69% less than the control) and the least chemical strength reduction after sulfate exposure (1.64% less than the control). The improvements are believed to be due to a combination of the physical void filling of the fine angular GMWT particle and secondary pozzolanic C-S-H formation in the ITZ and bulk paste.

It was observed that the 28-day compressive strength of the control was exceeded by GT30, and replacement levels up to 30% may be considered for structural application where 28-day compressive strength is the most important design consideration. At 56 days and 90 days' time, however, GT30 was below the control, and the optimum, based on the long-term performance, is clearly 20%. GT40 and GT50 should not be used for structural applications because they always have lower compressive strength at late age, higher water absorption and significantly lower chemical resistance.

The statistically significant interaction between GMWT content and curing age for the compressive strength verifies that the durability gain from the moderate level of GMWT replacement increases with age, as time-dependent pozzolanic hardening would expect. Two-way ANOVA followed by Tukey HSD showed that GT20 was a statistically different mix compared to GT0 and high replacement mixes (GT40, GT50) at the 95% confidence level.

On a practical level, the use of GMWT at 20% replacement in existing concrete production will not only help to decrease the reliance on natural river sand, but also enhance the economy of using local materials in small-scale construction activities in rural areas, while simultaneously reducing the uncontrolled accumulation of mining waste within the Talensi District. This would involve making quality control processes for the supply of GMWT, involving community participation to overcome barriers of awareness and acceptance, and regulatory procedures to ensure that the use of GMWT materials in construction is regulated.

Future research is needed on the following aspects: (i) full material characterisation of GMWT from Talensi and other artisanal mining sites in Ghana; (ii) extended tests for durability (chloride penetration, carbonation and long-term sulfate resistance); (iii) assessment of leaching of heavy metals; (iv) cost-benefit and life cycle

analysis; and (v) investigation of GMWT combined with supplementary cementitious materials for higher replacement levels to enhance reactivity.

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Author Contribution Statement

Conceptualisation: SAA (lead), PPY (equal), EK (supporting)

Data analysis: SAA (lead), EK (supporting)

Methodology: SAA (lead), PPY (supporting)

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The authors declare no known conflicts of interest associated with this publication.

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Reference

- Adamu, W., Edward, A., Emmanuel, A., & Osei, A. (2025). Evaluating the effect of different sand types on the physical, mechanical, and durability properties of sandcrete blocks in Ghana. *Journal of Building Materials and Structures*, 12(1), 35–48. <https://doi.org/10.34118/jbms.v12i1.4172>
- Adeyeye, R. A., Ikotun, J. O., & Otieno, M. (2024). Use of secondary gold tailings as fine aggregate in concrete. In *RILEM Bookseries* (pp. 560–571). https://doi.org/10.1007/978-3-031-75507-1_54
- Adiguzel, D., Tuylu, S., & Eker, H. (2022). Utilisation of tailings in concrete products: A review. *Construction and Building Materials*, 360, 129574. <https://doi.org/10.1016/j.conbuildmat.2022.129574>
- ASTM International. (2004). *Standard test method for density, relative density (specific gravity), and absorption of coarse aggregate* (ASTM C127-04). In *Annual book of ASTM standards*.
- British Standards Institution. (2002). *BS EN 1008:2002. Water for mixing concrete*. BSI.
- British Standards Institution. (2003). *BS EN 13529:2003. Products and systems for the protection and repair of concrete structures: Test methods—Determination of resistance to chemical attack*. BSI.
- British Standards Institution. (2004). *BS EN 1992-1-2:2004. Design of concrete structures—General rules—Structural fire design*. BSI.
- British Standards Institution. (2011). *BS 1881-122:2011. Testing concrete—Method for determination of water absorption*. BSI.
- British Standards Institution. (2013). *BS EN 12620:2013+A1. Aggregates for concrete*. BSI.
- British Standards Institution. (2019a). *BS EN 12390-3:2019. Testing hardened concrete: Compressive strength of test specimens*. BSI.
- British Standards Institution. (2019b). *BS EN 12390-6:2019. Testing hardened concrete: Tensile splitting strength of test specimens*. BSI.
- British Standards Institution. (2019c). *BS EN 12390-7:2019. Testing hardened concrete: Density of hardened concrete*. BSI.
- British Standards Institution. (2023). *BS 8500-2:2023. Concrete—Complementary British Standard to BS EN 206—Part 2: Specification for constituent materials and concrete*. BSI.
- Bureau of Indian Standards. (2000). *IS 456:2000. Plain and reinforced concrete—Code of practice*. Bureau of Indian Standards.

- Du, C., Wang, J., & Wang, Y. (2022). Study on environmental pollution caused by dumping operation in open pit mine under different factors. *Journal of Wind Engineering and Industrial Aerodynamics*, 226, 105044.
- García-Troncoso, N., Baykara, H., Cornejo, M. H., Riofrio, A., Tinoco-Hidalgo, M., & Flores-Rada, J. (2022). Comparative mechanical properties of conventional concrete mixture and concrete incorporating mining tailings sands. *Case Studies in Construction Materials*, 16, e01031. <https://doi.org/10.1016/j.cscm.2022.e01031>
- Gayana, S., & Chandar, A. K. (2018). Sustainable use of mine waste and tailings with suitable admixture as aggregates in concrete pavements. *Materials Today: Proceedings*, 5(1), 1771–1776.
- Hou, S., Guo, Y., Sun, J., Jiang, J., Gao, H., & Liu, J. (2025). Prospect of gold tailings as a new mineral admixture: Effect on hydration, pore structure and mechanical properties of concrete. *Materials Today Sustainability*, 29, 101078. <https://doi.org/10.1016/j.mtsust.2025.101078>
- Ikotun, J. O., Adeyeye, R. A., & Otieno, M. (2024). Experimental investigation on the effect of gold tailings as a partial replacement for sand in concrete. *Sustainability*, 16(17), 7762. <https://doi.org/10.3390/su16177762>
- Jayasimha, N., Sujini, B., & Annapurna, B. (2022). A study on durability and strength properties of high-strength concrete with partial replacement of iron ore tailings with fine aggregates. *Materials Today: Proceedings*, 65, 1922–1929. <https://doi.org/10.1016/j.matpr.2022.05.163>
- Khan, M., Patil, S. G., & Vaggappa, S. H. (2017). Preparation of concrete using goldmines waste. *International Journal*, 14(5), 20–25.
- Loksha, E. B., Aruna, M., & Reddy, S. K. (2025). Durability characteristics of geopolymer concrete produced using gold ore tailings along with recycled coarse aggregates. *Scientific Reports*, 15(1), 12051. <https://doi.org/10.1038/s41598-025-97056-6>
- Neville, A. (2000). Good reinforced concrete in the Arabian Gulf. *Materials and Structures*, 33, 655–664.
- Pitchaiah, P. S. (2017). Impacts of sand mining on environment: A review. *International Journal of Geoinformatics and Geological Science*, 4(1), 1–6. <https://doi.org/10.14445/23939206/ijggs-v4i1p101>
- Sambucci, M., & Valente, M. (2021). Ground waste tyre rubber as a total replacement of natural aggregates in concrete mixes: Application for lightweight paving blocks. *Materials*, 14(24), 7493. <https://doi.org/10.3390/ma14247493>
- Shettima, A. U., Hussin, M. W., Ahmad, Y., & Mirza, J. (2016). Evaluation of iron ore tailings as replacement for fine aggregate in concrete. *Construction and Building Materials*, 120, 72–79. <https://doi.org/10.1016/j.conbuildmat.2016.05.095>
- Song, Q., Zou, Y., Bao, J., & Zhang, P. (2024). Disposal of solid waste as building materials: A study on the mechanical and durability performance of concrete composed of gold tailings. *Journal of Materials Research and Technology*, 30, 2111–2124. <https://doi.org/10.1016/j.jmrt.2024.03.191>
- Tavakoli, D., Hashempour, M., & Heidari, A. (2018). Use of waste materials in concrete: A review. *Pertanika Journal of Science and Technology*, 26(2), 499–522.
- Xiao, H., & Falkner, H. (2006). Cement mortar with recycled concrete as aggregate. *Cement and Concrete Research*, 36(5), 905–913.