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The Potential of Using Waste Rock and Tailings from Gold Mining in Concrete Production

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ABSTRACT

In an effort to lessen the negative effects of mining on the environment and advance sustainability, this study explores the use of gold mining waste rock and tailings (GMWRT) as alternatives to conventional aggregates in concrete production. The study examined the chemical, physical, mechanical properties and water absorption of six concrete mixtures with varied levels of GMWRT (from 0% to 25%). X-ray fluorescence spectrometry and sieve analysis were used to determine the chemical composition and particle size distribution. After 28 days of curing, tests were conducted for compressive strength, flexural strength, and water absorption. The chemical analysis revealed that GMWRT had 80.37% SiO₂, Al₂O₃, and Fe₂O₃, exceeding the 70% pozzolanic material threshold established by ASTM C618. The findings showed that when GMWRT replaced conventional aggregates by 0 to 25%, the compressive strength (CS) went from 31.40 to 17.50 N/mm², which decreased as the proportion of the GMWRT increased. Although there was a decrease in compressive strength, the values fell within the acceptable range of 17 to 28 N/mm² for various applications. The flexural strength (FS) followed the same pattern as the CS, but it was higher than the required 3.13 N/mm², which means it can be utilised practicably. GMWRT concrete demonstrated enhanced resistance to chloride attack and reduced water absorption, making it viable for coastal construction. ANOVA and other statistical approaches revealed that the results were important. The analysis reveals that GMWRT can partially replace traditional aggregates. This is excellent for the economy and the environment. This method encourages environmentally friendly construction practices and offers developing nations like Ghana an eco-friendly way to handle mining waste.

1 Introduction

The rapid urbanization and infrastructural development of most countries have increased global demand for sustainable and affordable construction materials. Concrete is the most consumed man-made material, although there is currently growing

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concern over the high cost and environmental impact of its conventional constituents, namely cement and natural aggregates [1, 2]. This challenge is critical in many developing countries, where reliance on conventional materials like granite rock as coarse aggregates raises construction costs and significantly increases the potential for resource depletion [3-5]. Cost-effective and environmentally friendly alternatives to conventional concrete materials are a topical area of research interest globally [6-9].

The most promising options are the industrial by-products/waste materials, particularly from the mining industry. Gold mining, common in several countries including Ghana, generates considerable volumes of solid waste, mainly gold mining tailings and waste rock. These products, often disposed of around the vicinity of mining areas, contribute to environmental pollution and hence increase costs related to waste management [10-12]. Valorisation into construction materials provides one sure way of reducing these economic and environmental burdens with substantial benefits to mining stakeholders and the greater construction industry.

International research projects [13-15] have been conducted to investigate the feasibility of using different mining tailings such as molybdenum, phosphate, gold, copper, iron, zinc and oil sand as aggregates or supplementary cementitious materials in concrete and other applications. The above studies reveal a general trend that GMTs can affect the properties of concrete including compressive strength, water absorption and durability [9, 3, 16]. The CS can be improved by the addition of GMTs, in particular ground granulated blast-furnace slag; however it has often been recommended that the replacement of GMTs for fine aggregates should not exceed 30% to avoid any loss in strength [16, 17]. Nonetheless, some researchers reported that the use of GMTs as SCM decreases CS [7]. GMTs increase the water absorption of concrete owing to their finer nature and higher specific surface area [9, 16]. However, some researchers found that the substitution of GMTs for fine aggregates decreases the water absorption as a result of a pore-filling effect in the cement paste of concretes containing up to 80% of fine aggregate replacement [6, 18].

Apart from tailings, GMWR has also been investigated as a potential replacement for regular coarse aggregates in concrete. Studies have shown that GMWR can have a profound impact on the compressive strength of concrete [5, 19]. Previous studies have shown that the total replacement of natural aggregates with certain waste rocks, such as flint aggregate from phosphate waste, can lead to a sharp increase in compressive and flexural strengths [19]. Other tests have also demonstrated that the compressive strength of waste rocks concretes was equal to, or sometimes greater than, that of corresponding control mixtures [5]. Furthermore, the investigation of marble waste and waste ballast as coarse aggregates is part of a more comprehensive study of various other wastes, illustrating the possibility of improving both workability and mechanical properties of concrete [4, 20].

In spite of these promising results and obvious economic and ecological benefits associated with GMWRT, there is still a general scarcity of experimental studies in literature, especially with regard to their application as cementitious materials in green concrete production [21]. The heterogeneity of such minerals, sourced from different mining sites, requires further studies to be fully informed about their unique characteristics and how best their applications can be optimized in various uses. This is particularly so for countries like Ghana, where lack of specific information with respect to Ghanaian GMWRT for partial replacement of both natural sand and granite coarse aggregates has not seen its wide acceptance locally.

This paper, therefore, intends to study the mechanical performance of concrete produced using Ghanaian gold mining waste rock and tailings as partial replacements for fine aggregate, along with a partial replacement for granite coarse aggregate. The foreseen contribution to knowledge on the performance of GMWRT in concrete will spur sustainable building and efficient methods of utilizing mining waste materials, taking into perspective practical applications and solutions to reduce construction costs and further develop eco-friendly concrete production in Ghana and other developing countries facing similar resource challenges.

2 Materials and Methods

2.1 Materials

The main components used in the study included pit sand, granite coarse aggregate, gold mining waste rock, gold mining tailings (Figs. 1a-d), cement, and water. The binder utilized was ordinary Portland cement of class 32.5R CEM II/B-L (GHACEM) and was compliant with Ghana specification GS 1118:2016 [22]. The fine aggregates used were natural pit sands from Offinso in the Ashanti Region of Ghana and were within the requirement of BS 882 [23]. The fine aggregate of pit sand

used in this study was free from contaminants and within sieve sizes ranging from 0 to 4.75 mm, conforming to the specifications of BS 882 [23]. The coarse materials used in this study were crushed granites from a local quarry crushing facility in Ntesera, Ashanti Region, Ghana. The granites used were irregular and angular, of size 20 mm, conforming to BS 882 [23].

GMT and GMWR used in the study were supplied from the Shaanxi Mining Company dump site located in Tongo, in the Talensi District of the Upper East Region of Ghana. The tailings were used as a partial replacement for fine aggregates sizing 0 to 4.75 mm, conforming to BS 882 [23]. The waste rock was manually crushed to the required dimensions and used as a partial replacement for granite coarse aggregates, conforming to the requirement in BS 882 and Saturated Surface Dry (SSD) conditions. Portable potable water was obtained from the construction/wood laboratory, AAMUSTED University, Kumasi, Ghana.



Fig. 1- Sample of pit sand, crushed granite, goldmine tailings and waste rock from the source for the experiment

2.2 Determination of Chemical and Physical Property Tests

The chemical composition of the materials was investigated by X-ray fluorescence characterisation techniques (see Fig. 2a), in order to determine the oxide content of the tailings, Portland cement, and sand. The mineralogical composition and the concentration of heavy metals in the gold mine tailings were evaluated, as shown in Fig. 7 and Table 4.

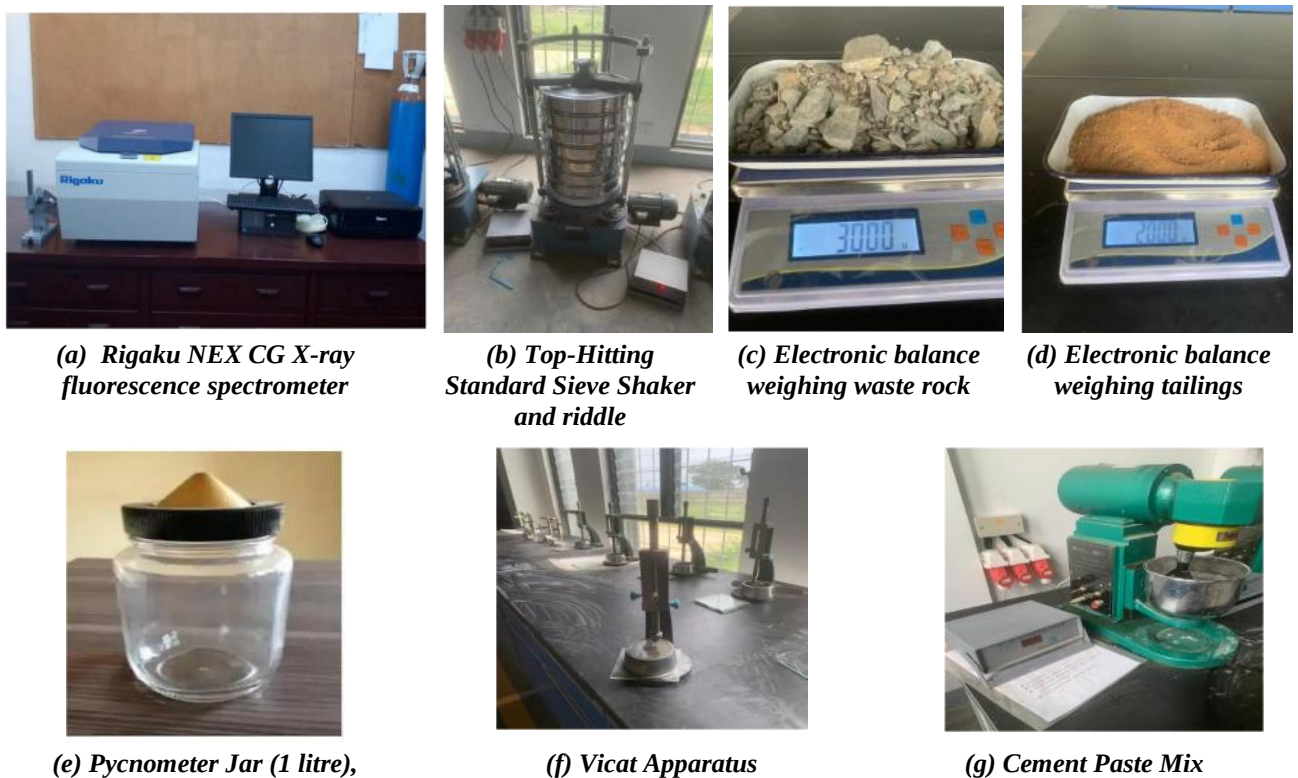


Fig. 2 - Apparatus for chemical and physical property tests

PSA was carried out for the physical property tests using a sieve analysis methodology and instrument. The apparatus used for the PSA consisted of a sieve shaker and a riddle controller (Fig. 2b). The natural sand, granite coarse aggregates, mining waste rock, and tailings were measured by means of an electronic balance (Figs. 2(c&d)). The PSD curves of the materials are presented in Fig. 8.

A 1-litre Pycnometer Jar (see to Fig. 2e) was used to determine the specific gravity (SG) of the cement, natural sand, granite coarse aggregates, and GMWRT. According to the proposed criteria, the specific gravity (SG) lies between 2.5 and 2.8 for fine aggregate and between 2.6 and 2.9 for granite coarse aggregate [24, 25].

A Vicat apparatus test (see Fig. 2f) was conducted on the cement to determine its standard consistency and the initial and final setting times. First, 32% water by weight was added to a 500 g sample of cement to prepare the cement paste and the mixture was mixed mechanically for 240 s. The results obtained at this water content were unsatisfactory. Therefore, the water content was systematically reduced to 30%, 28%, and finally to 25%, at which point satisfactory results were obtained.

2.3 Mix proportioning and designations

Mix ratios for the concrete were determined experimentally in this study based on the BS approach for concrete mix design [26]. Based on that, a mix ratio of 1:2:4 was selected for the concrete. Some trial castings with varying W/c ratios were prepared and cured for a 7-day period, and the W/c ratio that supplied maximum strength was used for the final castings. One reference mixture (control) was prepared with 100% cement, natural sand, and granite coarse aggregate, and 0% GMWRT. The GMWRT concrete mixes were prepared with waste rock and tailings contents of 5%, 10%, 15%, 20%, and 25%, using the same amount of cement, that is, 10 kg for each mixture. The mixing proportions are given in Table 1, and their descriptions are included in Table 2.

Table 1- Mix proportion for concrete materials

Mix design	Mix Ratio	Cement (kg)	Natural Sand (kg)	GMT (kg)	Natural Granite (kg)	GMWR (kg)	W/C
0%	1:2:4	10	20		40		0.6
5%	1:2:4	10	19	1	38	2	0.6
10%	1:2:4	10	18	2	36	4	0.6
15%	1:2:4	10	17	3	34	6	0.6
20%	1:2:4	10	16	4	32	8	0.6
25%	1:2:4	10	15	5	30	10	0.6

Table 2 - Mix designations

<i>Identity</i>	<i>Description</i>
C0	Concrete produced with 0% replacement of GMWRT
R5T5	concrete produced with 5% replacement of GMWR and 5% replacement of GMRT
R10T10	concrete produced with 10% replacement of GMWR and 10% replacement of GMRT
R15T15	concrete produced with 15% replacement of GMWR and 15% replacement of GMRT
R20T20	concrete produced with 20% replacement of GMWR and 20% replacement of GMRT
R25T25	concrete produced with 25% replacement of GMWR and 25% replacement of GMRT

2.4 Sample preparation

The processes for batching, mixing, and producing specimen cubes and beams were executed in compliance with the specifications provided in BS EN 14488–4 [27]. Alongside the control specimens, five concrete mixtures were formulated with partial substitutions of gold mine tailings for fine particles and waste rock for granite coarse aggregates. Cement,

aggregates, and water were batched by weight, as illustrated in Figs. 3(a–d). A laboratory pan mixer was used to mix the concrete, ensuring compliance with the BS standards, as shown in Figs. 3(e–h).



Fig. 3-- Batching and mixing material: (a) and (b) cement, (c) coarse aggregate, (d) water, (e) combination of material, (f) mixing in the process, (g) mixing of concrete, (h) concrete ready for use

The cubic and beam moulds, along with the samples used in the concrete production process, are shown in Figs. 4 (a–c). A total of 72 cube specimens, each measuring 100 mm × 100 mm × 100 mm, were cast, with 12 cubes for each of the six concrete mixes. Out of these, 54 cubes were used to determine the mean compressive strength (CS), and 18 were used for water absorption tests, in accordance with BS EN 14488-4 [27]. Additionally, 54 concrete beam specimens, each sized 100×100×500 mm, were prepared, with six beams for each of the nine concrete mixes (including the control and those containing GMWRT), to perform flexural strength (FS) tests as per BS EN 12390 [28].

After casting, the cube and beam specimens were demoulded (Figs. 4d & e) and submerged in a tank of clean potable water for curing, at intervals of 7, 14, and 28 days following the guidelines of ASTM C 309 [29], as illustrated in Fig. 4(f).



Fig. 4 - (a& b) Oiling of BS moulds 100x100x100 and 100x100x500 (c) specimen concrete inside cube mould, (d) specimen concrete out of cube mould, (e) specimen concrete beams (f) Specimen in a curing tank

2.5 Compressive Strength (CS) test

Compressive strength tests were conducted on hardened concrete specimens following 7, 14, and 28 days of damp curing, in line with BS EN 12390-3 [29]. A Hydro Servo Computer-Controlled Automatic 1000 kN Universal Testing Machine (UTM), depicted in Fig. 5 (a & b), was utilised for the testing. The load was incrementally and consistently applied at a rate of 140 kg/cm² per minute until each specimen experienced failure. The mean compressive strength was determined from three specimens for each mixture comprising 0% (control), 5%, 10%, 15%, 20%, and 25% Gold Mine Waste Rock Tailings (GMWRT), with the findings displayed in Table 6.

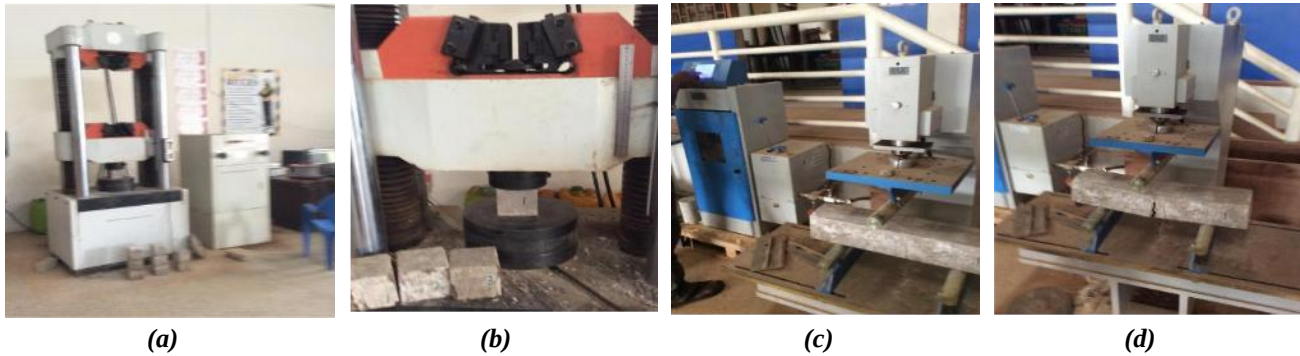


Fig. 5 - CS and FS tests (a) CS test set-up, (b) CS test in progress, (c) Flexural (3-point load) strength test set-up, (d) FS test in progress

2.6 Flexural Strength (FS) test

To quantify the resistance of concrete to bending stresses, a flexural strength test was conducted. The test specimens were cured and then dried before weighing and testing in accordance with BS EN 12390-5 [28]. The tests were conducted using an ELE flexural frame testing machine fitted with a 100 kN capacity. Each concrete beam was subjected to a central loading at mid-span with support at both ends as shown in Figures 5(c) and 5(d). The specimens were aligned properly with respect to the loading axis and the load applied gradually at a rate of 180 kg/cm² per minute until failure occurred. The results for the FS test are presented in Table 7.

2.7 Water absorption (WA) test

A physical property test was conducted to measure the water absorption (WA) and initial rate of absorption (IRA) of concrete to ensure that the material maintained the required engineering properties. The procedure for the water absorption test is shown in Fig. 6 (a, b, c) and it was performed after 28 days of curing. The WA test was performed according to the guidelines provided by BS 1881-122 [30], and a total number of 18 concrete cube specimens were used. These specimens underwent both water and air treatment. Initially, they were oven-dried for 24 hours at 0.5°C, while the ambient temperature was kept at 35°C. After drying, the specimens were allowed to cool down for another 24 hours and then stored in an airtight container. Once cooled, the specimens were weighed (see Fig. 6c), submerged in water for 60 minutes, then taken out, wiped and weighed again. Both the water absorption and the initial rate of absorption were measured. The WA test was also carried out in accordance with AS/NZS 4456.17 [31]. The water absorption was determined using Equation (1) and the IRA determined by using Equation (2). In each of the concrete mix combinations, three specimens were used to be tested for both WA and IRA.

$$WA = \frac{100(m_i - m_f)}{m_i} \% \quad (1)$$

$$IRA = \frac{1000(m_{f,60} - m_i)}{A} (\text{kg/m}^2/\text{min}) \quad (2)$$

Where m_i is the mass of the oven-dried specimen (g), m_f is the mass of the specimen after 24 h of immersion in water (g), $m_{f,60}$ is the mass of the specimen after immersion of the bottom 3 mm in water for 60 s (g), and A is the bottom surface area of the specimen (mm²).

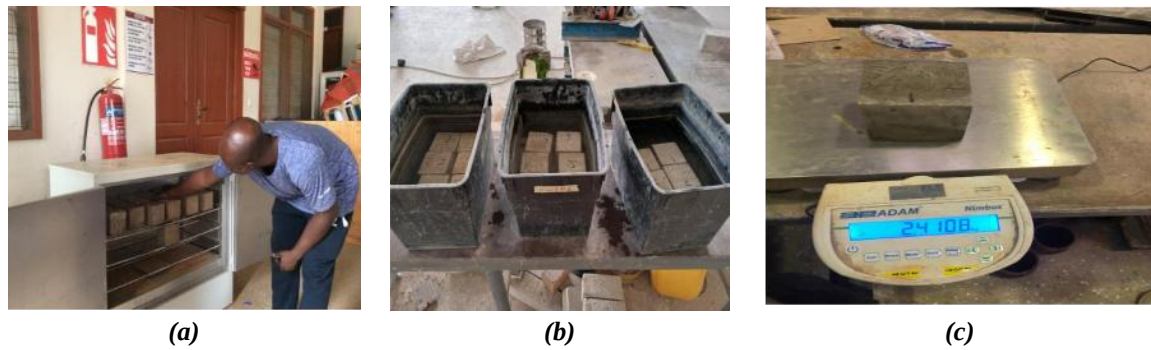


Fig.6 - (a) Oven drying samples for testing, (b) Cubes submerged in water, (c) Weighing of cubes after submerged in water.

2.8 Statistical Analysis

The mean values of the compressive and flexural strengths related to the conventional concrete and the percentage of replacement of gold mining waste rock and tailings were determined using the Statistical Package for Social Science (SPSS), version 22. The data are also presented in graphical visualisations. ANOVA was used to determine significant differences and variations between the test results.

3 Results and Discussion

3.1 Chemical Composition of GMWT, Cement and Sand

Table 3 - Chemical Composition of the gold mining waste tailings, cement, and sand

Oxide	SiO ₂	SO ₃	Fe ₂ O ₃	Cl	K ₂ O	Al ₂ O ₃	MnO	Na ₂ O	TiO ₂	MgO	ZnO	CaO	Cr ₂ O ₃
Tailings (%)	46.36	2.99	24.81	0.03	0.71	9.2	0.06	1.20	0.41	0.62	0.13	13.2	0.23
Cement (%)	30.3	3.31	5.13	0.05	1.32	11.4	0.44	0.53	0.74	2.64	0.011	43.9	0.02
Sand (%)	90.12	0.05	0.68	0.03	1.30	3.91	0.03	0.05	0.83	0.13	-	0.48	0.03
Pozzolanic	SiO ₂ + Fe ₂ O ₃ + Al ₂ O ₃ = 80.37%; LoI 12.5												

Table 4 - Heavy metal content GMWRT

Heavy metal (mg/kg)	Gold tailings (wt%)
Zn	28.5
Pb	60
Cr	8
Cu	34
Cd	0.33

The chemical composition of GMT presented in Table 3 indicates that the major oxides present in the tailings are SiO₂, CaO, Al₂O₃, and Fe₂O₃. The sum of the percentages of the main components of gold mining rock tailings (SiO₂ + Al₂O₃ + Fe₂O₃) is 80.37%, well above the ASTM C618 [32] limit of 70% for pozzolanic materials. This indicates that GMT has great potential as a supplementary cementitious material in green concrete production. These results are consistent with the chemical composition of gold tailings reported by other studies [21, 33-35]. Although the sum of these oxides does not confirm pozzolanic activity, it is a strong indicator of the suitability of the material for such purposes.

This explains that while the oxide total is an important indicator, it is not the only predictor of pozzolanic properties. The physical and mechanical properties of GMWT satisfy the requirements set out in ASTM C618. XRD results presented

in Fig. 7 reveal that GMWT is primarily made up of volcanic minerals that have amorphous structures and include muscovite, pyrite, and quartz. It has a basic composition with high quartz levels, SiO_2 , and Fe_2O_3 .

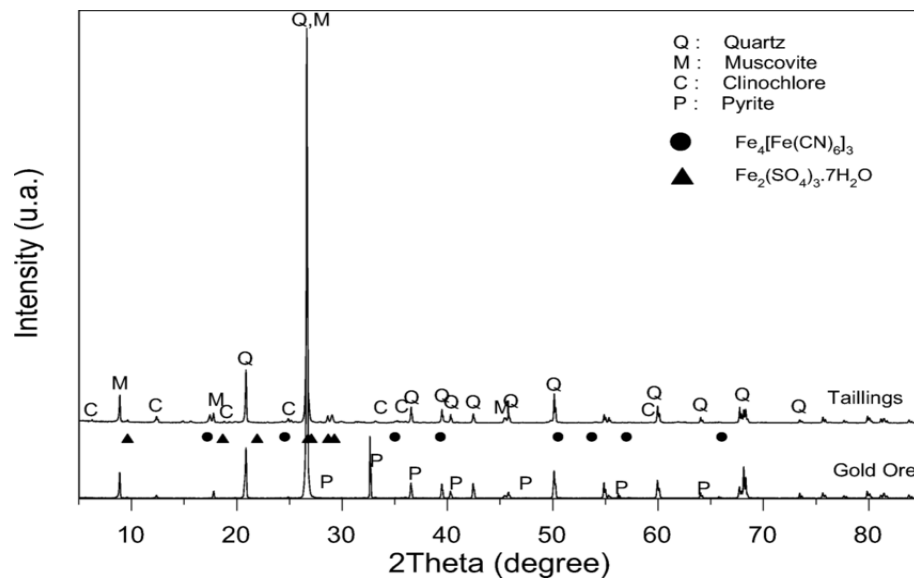


Fig. 7 - XRD analyses of the mineral content of the GMWT

The major oxide constituents of Portland cement were CaO (43.9%) and SiO_2 (43.3%); accordingly, GMWT consisted of CaO (14.87%) and SiO_2 (46.36%). Table 4 shows the heavy metal content of the gold tailings. Several studies [15, 36, 37] have shown that the presence of heavy metal ions has a negative effect on the fresh properties of concrete due to causing delayed hydration, which could lead to a reduction in the setting time. The low heavy metal content within the gold tailings made the aforementioned effects insignificant for our study.

3.2 Physical properties of GMWRT

According to Table 5, the FM of tailings was 2.32 and that of waste rock was 3.0. The fineness modulus of fine aggregate was 3.6, while the FM of granite coarse aggregate was 5.4. Figure 8 shows the size distribution of these materials.

Table 5 - Physical properties of aggregates and cement

Properties	Result
Standard consistency test	25%
Initial setting test	2hrs, 25mins
Final setting time	3hrs, 55mins
SG of cement	3.10g/cc
Soundness of cement	4mm
SG of fine aggregate	2.45
SG of coarse aggregate	2.72
SG of goldmine waste tailings	2.65
SG of goldmine waste rock	2.50
FM of fine aggregates	3.6
FM of coarse aggregates	5.4
FM of goldmine tailings	2.32
FM of gold mine waste rock	3.0

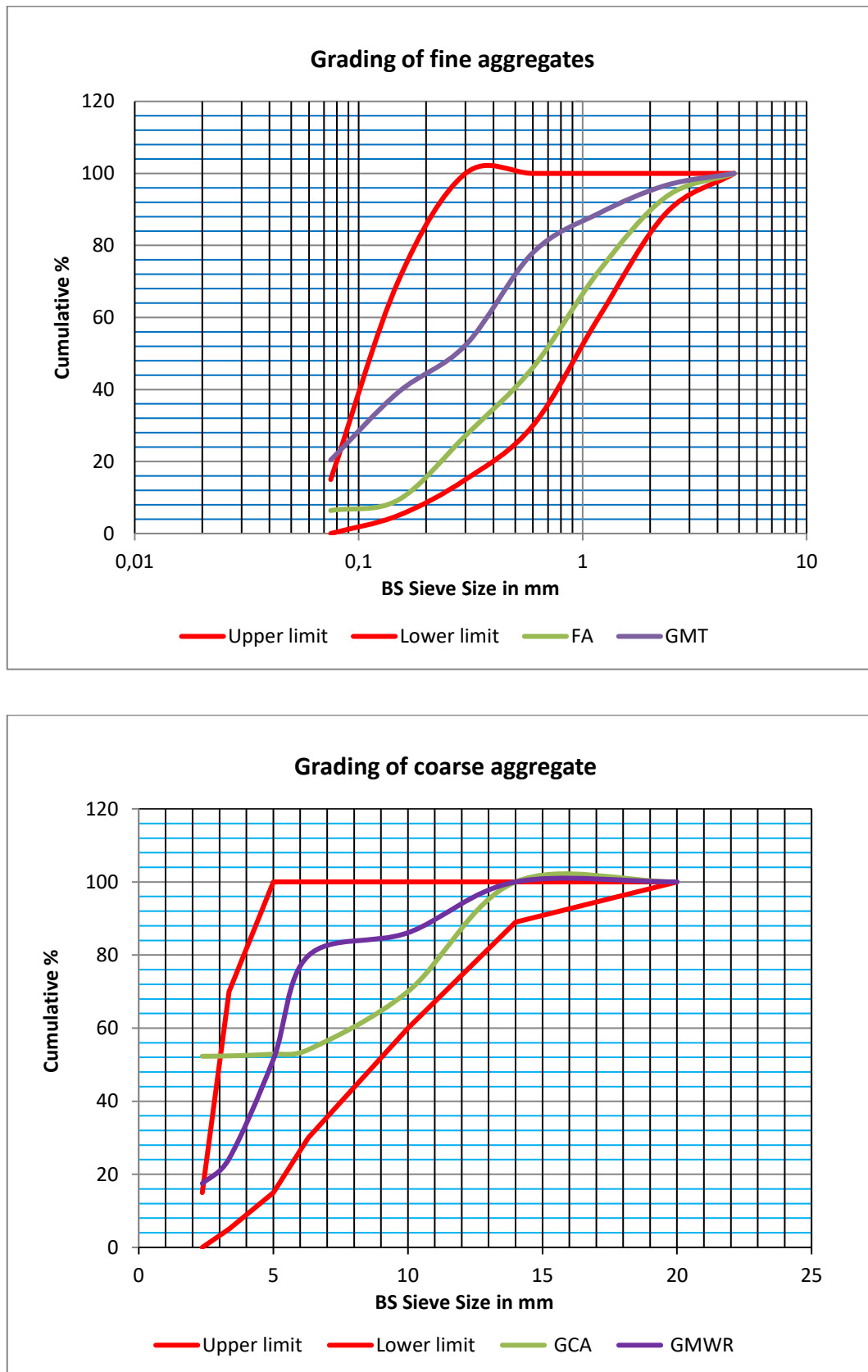


Fig. 8 - Particle size distribution (PSD) curve of concrete materials

Note: Sand is fine aggregate (FA), gold mine tailings, (GMT), gold mining waste rock (GMWR), and granite coarse aggregate (GCA)

According to ASTM C33/C33M [24], the ideal range of FM for a fine aggregate is between 2.3 to 3.1. Therefore, the fineness modulus of the tailings, with a value of 2.32, falls into the necessary FM range and within the Zone II criteria, which assures a well-graded material that can be worked with in compliance with the character of concrete mixture. Such a form of distribution, on the one side, provides greater density to a fresh concrete mixture due to the small particles filling in the spaces between the larger particles. On the other hand, it results in the fresh concrete mix sticking together with better flow. The FM for the standard fine aggregate was 3.6, a high value for coarser sands. It may not work unless with the addition of extra water and other things.

While the FM value for granite coarse aggregate is 5.4, lower than the range for coarse aggregates, ranging from 6.0 to 6.9, it is, therefore, a finer material [38]. A FM value of 3.0 for waste rock aggregate is considerably lower than this range and will thus not be suitable for structural concrete. All metamorphic rocks, of which quartzite is a type of waste rock, contain many pores, making them more susceptible to compaction by the application of pressure. [39]. This could make the concrete weaker and less long-lasting.

Smaller-sized coarse particles may alter the fitting of the concrete matrix, hence affecting the strength of the matrix. Coarser aggregates strengthen the particles through better fitting, but could require additional water or plasticisers to function effectively [40]. The size and morphology of the aggregates, as well as their mineral content, should be considered when manufacturing concrete using various resources, such as mining waste rock and tailings. Specific Gravity (SG) measures how dense a substance is compared to water, which has a big effect on the quality of the concrete that was created from it during construction [41]. According to ASTM C33/C33M [24] and ASTM C136 [25], fine aggregate had a specific gravity (SG) of 2.45, while granite coarse aggregate had a specific gravity of 2.72. The readings were in the range of 2.5 to 2.8 and 2.6 to 2.9, which is fine. The specific gravity of the gold mining tailings, on the other hand, was 2.65, which is within the acceptable range. The waste rock, on the other hand, was 2.50, which is lower than both granite coarse aggregate with an SG of 2.72 and the suggested range. This could change how dense and easy to deal with concrete is. The tailings have a specific gravity of 2.65, which is a bit higher than usual. Their density was the same as that of other aggregates, which means they may be utilised in concrete mixtures instead of ordinary aggregates. Goldmine tailings have a high specific gravity because they have a lot of SiO_2 and Fe_2O_3 . The relatively high SG [15] is also due to the presence of heavy minerals such pyrite and magnetite, even though they are in minor amounts. The waste rock would have a lower specific gravity than the granite coarse aggregate, which means that the rock mass has bigger voids. Standards like ASTM C188 [42] and ACI 221R-14 [43] say this. The specific gravity of the waste rock varies significantly according on the rock type; still, an SG of 2.65, as indicated in Table 5, is characteristic of the majority of natural rocks. To make cement with the right consistency, you need a lot of water—0.6. The 25% result of a typical consistency test in this work is in line with ASTM C187 [44], which says that the normal consistency of cement should be between 25% and 35% water. The final setting test showed that the cement sets swiftly, in 3 hours and 55 minutes. The early setting test gave the results that it sets moderately, in 2 hours and 25 minutes. These attributes made the placement of concrete at the time of construction much easier. The specific gravity of the cement was found to be 3.10 according to ASTM C188-17 [42], lying in the usual range for Portland cement, which is from 3.10 to 3.16. It depicts that the cement now is denser as compared to the virgin state, as highlighted in Table 5. This could be bad regarding compressive strength and workability. The soundness of cement provides information about the quality of maintaining its shape during the wet state. The cement soundness value of 0.4 cm shows that there is very little chance of break or fault occurrence.

3.3 Compressive Strength (CS)

The results of the CS test, showing how CS varies across different curing times and percentages of GMWRT substitutions in concrete manufacture, are presented in Table 6 below. The values derived from the partial replacement of GMWRT by waste rock at 5%, 10%, 15%, 20%, and 25%, respectively, consistently fell within the prescribed values of 17 N/mm² to 28 N/mm² for residential and commercial structures as delineated by BS EN 12390-3 on the 28th day. The concretes made using waste rock and tailings from the Shaanxi gold mining firm in Tongo can therefore be used at construction sites for typical construction. The 28-day CS of the control mix (0%) was the highest value of 31.4 N/mm². This represents an increase of 13.4%, 21.97%, 29.94%, 37.26%, and 44.27% compared to the 5%, 10%, 15%, 20%, and 25% replacement of GMWRT at 28 days, which recorded CS values of 27.2 N/mm², 24.50 N/mm², 22.0 N/mm², 19.70 N/mm², and 17.50 N/mm², respectively.

Table 6 - Difference in Mean CS of control and GMWRT concrete specimens

Mix design	Mean CS of materials (N/mm ²)		
	7 days	14 days	28 days
Control 0%	20.5±1.37 ^A	27.5±1.00 ^A	31.40±1.58 ^A
Replacement 5%	17.8±1.89 ^{AB}	22.9±0.44 ^{BC}	27.2±1.23 ^{AB}
Replacement 10%	16.3±0.88 ^{AE}	19.4±5.73 ^{AD}	24.5±0.74 ^{AC}
Replacement 15%	14.3±0.69 ^{AC}	16.6±0.87 ^{CE}	22.0±1.57 ^{AD}
Replacement 20%	11.6±0.84 ^{AD}	14.5±0.18 ^{AF}	19.7±0.89 ^{AF}
Replacement 25%	10.8±0.60 ^{AF}	15.0±0.36 ^{AG}	17.5±0.40 ^{AE}
p Value	0.000	0.004	0.000

Note: Means in the same column followed by the same letter(s) are statistically significant at ($P \leq 0.05$)

Additionally, it is clear that all of the concrete mixes in this study that used gold mining waste showed a drop in compressive strength as the replacement % went up. Additionally, statistical analysis using One-Way ANOVA showed that the compressive strength of the specimens varied a lot ($p = 0.000$) after 7, 14, and 28 days of curing compared to the control mix. This indicates that the length of curing influenced the development of compressive strength in the concrete sample. The Tukey HSD analysis showed that although while the One-Way ANOVA showed that there were significant differences, not all mix designs were statistically different from one another (Table 6). The data suggest that replacing fine and granite coarse aggregates with GMWRT in concrete production may lead to a decrease in compressive strength when compared to the control group that did not incorporate GMWRT. These results typically align with extensive experimental studies demonstrating that CS decreases as the volume of mining tailings grows across various categories. [11, 16, 19]. The results of this study on gold tailings reveal an inverse relationship between CS and the rising amounts of gold tailings, corroborating the findings of other researchers. This study saw a reduction of up to 44.3% at a substitution level of 25% GMWRT, while [45] reported a gradual decrease in the compressive strength of concrete with rising percentages of IOT, from 20% to 40% replacement. A study showed that CS could drop by as much as 17% with a 25% replacement rate. [16] observed a decrease in the compressive strength of concrete with a 30% replacement of gold mine waste. Additionally, [46] found that the number of gaps in concrete went down a lot when the gold ore tailings were finer. This means that gold mining tailings might be used as a replacement in concrete making up to 20% of the total.

In this regard, [47] observed that increasing the amount of gold mining waste rock and tailings to 30% reduces the compressive strength of concrete. A study by [48] also reported that as the concentration of tailings increases by 10%, the compressive strength of tailings concrete decreases. In another similar study that focused on investigating the effects of iron ore tailings on the quality of concrete, it was also established that with an increased tailings replacement, the compressive strengths were reduced. Note herein that a reduction of consumer surplus by GMWRT may be minimized by optimizing the mix proportions and curing conditions. In this line, a study by [49] investigated the influence of mix proportions and curing conditions on the compressive strength of concrete made with waste rock as partial replacement to standard recycled aggregate concrete. The results indicated that the compressive strength of concrete can be possibly improved by using an appropriate combination of gold mining waste rock and tailings as partial replacement to natural or recycled aggregates with favorable curing conditions.

These have three important implications for the use of GMWRT in concrete manufacturing: first, the replacement ratio of GMWRT should be minimized in pursuit of high compressive strength; second, further studies and optimization should be carried out to determine the optimal GMWRT replacement that can balance strength with utilisation of waste material in the manufacturing of concrete; and third, optimum performance could only be achieved if great care is paid to the intended strength and calibration of the ratio of GMWRT replacement.

3.4 Flexural Strength (FS)

The trend of FS for different curing durations and varied percentages of GMWRT substitution, as shown in Table 7, shows that the control group (0% GMWRT) had the highest average FS after 7, 14, and 28 days compared to all partially

replaced specimens. The highest flexural strength of 4.40 N/mm² for the 0% control mix was 2%, 2.73%, 5.23%, 13.64%, and 21.14% higher than the GWRT combinations (5%, 10%, 15%, 20%, and 25%) that had 4.3 N/mm², 4.2 N/mm², 4.0 N/mm², 3.7 N/mm², and 3.5 N/mm² at 28 days, respectively. Even though these differences were clear, a one-way ANOVA test did not show any significant differences between the tested specimens for all of the curing ages that were looked at. The p-values for 7, 14, and 28 days were 0.124, 0.439, and 0.574, respectively. This means that when the number of curing days went up, the failure strength of specimens created using GMWRT was not very different from that of control specimens.

Table 7 - Difference in Mean FS of control and GMWRT concrete specimens

Mix design	Mean FS of materials (N/mm ²)		
	7 days	14 days	28 days
Control 0%	3.8±0.96	4.0±0.96	4.4±0.10
Replacement 5%	3.7±0.15	3.8±0.21	4.3±0.36
Replacement 10%	3.5±0.23	3.7±0.46	4.2±0.26
Replacement 15%	3.3±0.13	3.6±0.17	4.0±0.56
Replacement 20%	2.5±0.21	3.0±0.25	3.7±1.66
Replacement 25%	2.4±0.35	2.7±0.03	3.5±0.57
p Value	0.124	0.439	0.574

Note: p-values statistically significant at 0.05

The data indicate that with an increased dosage of GMWRT, the FS decreased throughout all curing periods, namely, 7, 14, and 28 days. Therefore, the FS provided a trend similar to that obtained from the compressive strength. Even though the FS decreases as the GMWRT mix proportion increases, there exists a peak in the FS of GMWRT concrete (5%, 10%, 15%, 20%, and 25%) which is above the standard requirement of 3.13 N/mm² specified by IS 456- [50]. The present results are in agreement with those reported in the literature using mining waste rocks and tailings as partial replacements in concrete production. In this regard, [47] observed a slight reduction in the compressive strength of concrete as the amount of gold mining waste rock and tailings increased at a substitution level of 30%. A different study conducted by [9] indicated that the splitting tensile strength of concrete decreased with the increased amount of gold tailings. At 75% and 100% replacement levels, it was reported that the strength decreased by up to 4.35% and 15.53%, respectively, compared to GT0%. [47] obtained a reduction in the flexural strength of concrete upon the addition of 30% gold mining waste. [45] The study described that the compressive strength and flexural strength were only marginally lower at replacement levels higher than 20% to 40% of IOT. [51] reported that the fire strength of the burned bricks decreased when the content of the ground material waste residue was increased. Higher replacement percentages of GMWRT resulted in a decrease in FS.

These results suggest that the utilization of GMWRT as a replacement for fine and coarse aggregates in concrete production may negatively affect the FS of final products. The results revealed that the use of GMWRT to produce concrete should be cautiously considered concerning strength requirements for the construction. While FS remains an important aspect of the application, the GMWRT replacement ratio should be kept at a minimum to achieve acceptable strength. Changes in mix design and curing regimes through incorporating admixtures could potentially be employed to reduce the loss of FS due to GMWRT.

3.5 Water Absorption (WA)

The water absorption (WA) of concrete contributes to the lifespan (durability) of construction structures. The durability of concrete depends on the degree of exposure, concrete grade (or strength), and cement content. Water absorption (WA) and initial rate of absorption (IRA) results in Fig. 9 indicate that on the 28th day, WA with 5% replacement was 0.19 %, 10 % replacement had a WA of 0.4%, 15% replacement had a WA of 0.6%, 20% replacement had a WA of 0.8%, and 25% replacement had a WA of 1.0%. Also, 5% replacement had an IRA of 0.02 kg/m²/min, 10% replacement had a 0.04 kg/m²/min, 15% replacement had a 0.06kg/m²/min, 20% replacement had a 0.08 kg/m²/min, and 25% replacement had a 0.1 kg/m²/min. From the WA and IRA trends in Fig. 9, it can be observed that WA and IRA for the 5% to 25% GMWRT-based concretes were generally higher than those of normal concrete (0%), but lower than the recommended threshold of 1.5% [5,

16]. Similarly, [6] observed that fine particles from GMWRT were likely to fill micro-voids in concrete, resulting in reduced 28-day water absorption (WA) and initial rate absorption (IRA). In coastal areas, concrete with a WA of less than 2% is considered durable for construction projects with a fifty-year design life [52]. Therefore, it is suitable to use these materials to develop concrete for use in the construction industry. These findings are consistent with those of previous studies [16, 53].

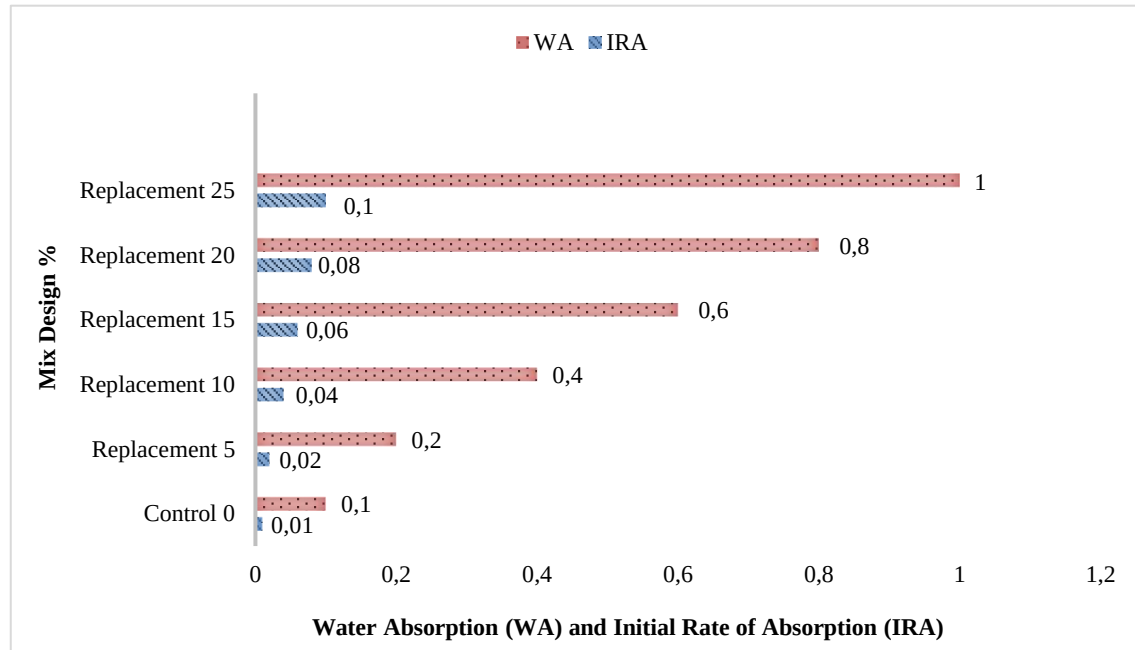


Fig. 9- Water absorption and initial rate of absorption results of GMWRT concrete

4 Conclusion and summary of findings

This study aimed to investigate the potential of using Gold Mining Waste Rock and Tailings (GMWRT) from the Shaanxi mining firm in Tongo, Ghana, as a partial replacement for fine and coarse aggregates in concrete.

Main Finding

The research work undoubtedly established that the GMWRT from the Shaanxi mining firm located in Tongo, Ghana, is a feasible and efficient material for the partial replacement of aggregates in concrete production to achieve sustainability and cost-effectiveness in building construction.

Key Findings:

1. GMT is a chemically inert material comprising major oxides such as SiO_2 , CaO , Al_2O_3 , MgO , and Fe_2O_3 . The sum of SiO_2 , Al_2O_3 , and Fe_2O_3 is 80.37%, which is greater than the requirement of 70% for pozzolanic materials (ASTM C618), showing that GMT is appropriate for green concrete production as a supplementary cementitious material.
2. The specific mass of the GMT was found to be 2.54 g / cm^3 , fairly similar to that of natural sand, that is, 2.45 g / cm^3 . GMT can thus be used as a substitute for natural sand without treatment. The particle size distribution of the GMWRT turned out not to be as good as that of natural aggregates, although still within the recommended ranges.
3. Compressive strength of the concrete decreased with the increase in the percentage of GMWRT. However, concrete mixes containing up to 25% replacement of GMWRT satisfied the minimum requirements of strength (17 N/mm^2 to 28 N/mm^2) at 28 days as per BS EN 12390-3 [40].
4. Despite the fact that there was a marginal reduction in flexural strength with an increased percentage of GMWRT replacement, all the GMWRT specimens satisfied the standard requirement of 3.13 N/mm^2 (IS 456) [50, 52]. This can prove that better flexural strength in concrete can be achieved using GMWRT as partial replacement.
5. GMWRT coarse aggregate concretes showed improved durability, especially in terms of chloride attack resistance and water absorption. In particular, the water absorption for the 5% - 25% GMWRT concretes was below the

recommended 2% threshold for the concretes to be used in coastal areas, therefore achieving their design life of fifty years.

Further research is indispensable to achieve a deeper scientific understanding and optimization of the various types of gold tailings for their respective applications. This will widen its adoption and utilization in construction in a more customized manner.

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