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PERFORMANCE OF CONCRETE INCORPORATING NICKEL SLAG AND GOLD TAILINGS AS PARTIAL REPLACEMENT MATERIALS

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ABSTRACT: The growing scarcity of natural sand and the increasing environmental cost of cement manufacturing have led to a growing interest in the use of industrial by-products as constituents of concrete. This study investigates fine nickel slag (FNS) and gold tailings (GT) as partial replacements for fine aggregate and cement, respectively, in conventional concrete, with the dual objective of reducing mining and metallurgical waste generation and reducing pressure on virgin resources. In Indonesia, the minimum compressive strength of concrete for residential use is 21 MPa. The possibility of fulfilling this criterion to the advantage of the environment and economy was investigated by replacing 5-25% of the cement and sand with GT and FNS. Having characterized the physical and chemical characteristics of the raw materials, six concrete mixes, a reference, and GT5 to GT25, were made and evaluated for workability, compressive and tensile strength, porosity, and gas permeability. Workability was drastically reduced with the substitution levels. The slump value decreased from 80 mm for the control mix to 26 mm for 25% replacement. Similarly, compressive strength decreased, but the best result among the replaced mixes was GT5, with 38.03 MPa at 28 days, comfortably exceeding the Indonesian requirement. The tensile strength also exhibited a similar decreasing pattern, with the maximum reduction at 25% replacement. In summary, it is proposed that FNS and GT may be implemented in the standard concrete manufacturing with acceptable structural performance and therefore provide a more sustainable and waste-conscious method.

Keywords: Concrete, Fine nickel slag, Gold tailing, Porosity, Workability

1. INTRODUCTION

As construction is accelerated around the world, concrete is still relied upon as the backbone of building. It is valued for being durable, adaptable, and fairly inexpensive, and for that reason, it is used everywhere from homes to transport networks to industrial sites. This dependence, however, is paid for at an environmental cost. When ordinary concrete is produced, large amounts of natural sand, gravel, and portland cement are consumed, and the making of that cement is recognized as one of the biggest sources of carbon emissions, while considerable damage is also done to the landscape. The tension is felt most sharply in rapidly urbanizing countries such as Indonesia, where building demand keeps being driven upward even as riverbanks are eroded, and biodiversity is lost in the regions where aggregates are extracted [1][2]. Because of all this, the search for alternatives to both aggregates and binders has been intensified, so that dependence on virgin natural resources can be reduced without structural performance being compromised.

A parallel opportunity is also offered by the mining and metallurgical sectors, where by-products such as ferronickel slag and gold tailings are generated in large volumes. As the world's largest nickel producer, Indonesia itself is left with more than 13 million tons of nickel slag each year, much of which is simply left underused in disposal sites, where the risk of heavy-metal leaching and water pollution is raised whenever it is poorly treated [3]. A similar legacy has been inherited from gold mining, where enormous quantities of tailings are piled up, often laced with chemical residues that must be looked after for the long term. When these materials are put to use as mineral additives or as a substitute for aggregate in concrete, two problems can be tackled at once: the environmental burden of waste disposal is eased, while some of the pressure on natural aggregate extraction is relieved [4][5][6][7]. It is this twofold benefit that has driven a growing body of research into the use of nickel slag and gold mine tailings as functional replacements for the natural materials normally relied upon in concrete production.

Nickel slag, which is itself produced as a byproduct of nickel smelting, has been given particular attention as a replacement for both fine and coarse aggregates. Its angular particle shape, high density, and crystalline microstructure have been found to contribute favorably to strength development [8][9], and when optimized substitution levels are used, improved flowability and mechanical performance have been observed in self-compacting and high-performance concrete mixtures [1]. Taken together, these findings point to a material by which natural aggregates may be replaced without structural integrity being lost.

A complementary potential is offered by gold tailing (GT). Because the material carries a chemical profile rich in silica, alumina, and other oxides, it is found to be widely compactible with cementitious materials. Considerable interest has been drawn to the clean use of this waste stream, which is regarded as a sustainable way of managing it [10]. In several experiments, it has been shown that part of the cement or fine aggregate can be substituted by GT, by which particle packing is improved, and the environmental impact of concrete manufacturing is reduced [7][11]. In a similar vein, it was reported by Chen et al. [8] that mechanical performance is enhanced when gold tailings are incorporated into concrete at an optimum ratio, although workability and hydration can be adversely affected when the replacement level is set too high. Nickel slag, when used as coarse aggregate, has also been shown to carry the potential for compressive strength to be increased as the slag concentration is raised, and for that reason, it can be relied upon as an alternative to gravel [11]. This body of work, taken together, has identified gold tailings as a potential choice for low-carbon cementitious and additional cementitious applications [12][13].

Besides the conventional concrete, ferronickel slag used as fine aggregates has enhanced the properties of self-compacting concrete in both fresh and hardened states, strengthening the argument for its use as a viable material for sustainable construction [9][14]. Similar industrial by-products incorporated in geopolymer concrete have also shown high compressive strength and durability in various construction works [15].

However, there are still substantial gaps in the literature. Nickel slag and gold tailings have been mostly examined individually. Not many studies have been carried out to study the effects of these materials while replacing cement and fine aggregate concurrently. The conventional, non-geopolymer concrete applications are still underexplored, particularly those regulated by Indonesian structural standards that require a minimum compressive strength of 21 MPa for residential buildings. Comparative research on the combined effects of FNS and GT on durability indicators such as porosity and permeability, which ultimately regulate long-term performance, is also rare.

Together, these findings confirm that recycling ferronickel slag into concrete production already provides established environmental, economic, and even mechanical benefits over traditional aggregates [4][16][17], a track record that strengthens the case for testing it alongside gold tailings in the present study.

Based on this, the present study analyzes the combined use of fine nickel slag (FNS) as a substitute for fine aggregate and gold tailings (GT) as a partial substitute for cement, in comparison with a reference concrete mix (Ref). The 5–25% substitution range was selected to encompass the levels most frequently cited as effective in the nickel slag and gold tailings literature. Below 5%, the environmental and economic benefit of waste utilization becomes marginal, while substitution levels beyond 25% have been associated in previous studies with disproportionate losses in workability and strength that compromise practical applicability. Within this range, the combinations are designated as GT5, GT10, GT15, GT20, and GT25, by which the simultaneous replacement of 5%, 10%, 15%, 20%, and 25% of the cement by GT and of the sand by FNS is represented. The workability, compressive strength, tensile strength, porosity, and permeability of the mixes are then evaluated, so that the substitution level by which structural performance and sustainability objectives are best balanced can be identified.

The novelty of this work is its simultaneous multi-waste substitution strategy, its direct relevance to Indonesia's waste utilization policy, and its contribution to understanding how mixed metallurgical and mining by-products interact within a single concrete matrix at the mechanical and microstructural level. Besides the immediate findings, the study gives practical guidelines for sustainable building practice to reduce strain on natural resource extraction, while promoting ecologically responsible waste management.

The rest of this paper is organized as follows: Section 2 presents the research significance of using

FNS and GT as simultaneous substitutes, Section 3 describes the materials, experimental design, and mix proportions used in this study, Section 4 reports and discusses the results of workability, mechanical, and durability testing, and Section 5 concludes with the key findings and recommendations for future research.

2. RESEARCH SIGNIFICANCE

The novelty of this research is not only to consider fine nickel slag (FNS) and gold tailings (GT) together as partial replacement of cement and fine aggregate in conventional concrete, but also that it is considered separately as in previous studies. Considering the investigated replacement levels, the 5% mixture (GT5) is the most balanced one, providing the maximum compressive strength of the substituted mixes, while lowering the dependency on virgin resources and the mining waste. These results provide a feasible, sustainable technique for concrete manufacturing and add fresh evidence to the mechanical and durability behavior of multi-waste mixed concrete.

3. EXPERIMENTS AND METHODS

3.1 Materials

The experimental design used the Indonesian National Standard. [18]. Method for determining the appropriate cement-concrete ratio by substituting equal quantities of cement with gold tailing (GT) and fine nickel slag (FNS). This permits a systematic study of the effect of GT and nickel slag on altering the properties of concrete. The composition was created using GT and nickel as a reference in normal concrete mixes. The proportions of the mix are listed in Table 3 where GT and Nickel are used as replacements for cement and sand up to 25%.

A concrete mixer is used to mix gravel, sand, cement, GT, and FNS for 1 min before water is added to make a homogeneous concrete. Then, a workability test is performed using the slump test technique with Abrams' cone, according to ASTM C143/C143M-15 [19]. The liquid is then poured into the mold and allowed to set for 24 hours. It is then water cured (water curing) for 7, 14, or 28 days. Then it is evaluated for its compressive and tensile strength for 28 days.

3.2 Experimental Design

Sieve analysis is a fundamental civil engineering test conducted as per ASTM C136/C136M [20] to find the particle size distribution of aggtegated. In this test, a sample of dry aggregate is sent through a stack of sieves with mesh sizes decreasing in size from coarse to fine. Each sieve captures particles in a certain size range, and the material collected on each sieve is computed and shown. This is called a gradation curve. This test helps to evaluate the aggregate's appropriateness for usage in concrete, asphalt, and other building products. Generally, a well-graded aggregate with a combination of varied particle sizes offers superior compaction, stability, and strength in building applications as indicated in Table 1 [1]. The specific gravity test, performed according to ASTM C128 [21], is used to assess the density of aggregates compared to water.

The test procedure is to oven-dry a sample of the aggregate, weigh the sample, and then soak it in water for 24 hours to obtain a state that is saturated surface-dry (SSD). The surface moisture is then removed, and the sample is reweighed in the SSD condition. Next, the sample is submerged in water and weighed once more. The specific gravity is calculated from the sample's dry weight together with the difference between its SSD and submerged weights, as given in equation (1)

$$\boldsymbol{F} = \frac{\boldsymbol{C}}{\boldsymbol{C} - \boldsymbol{E}} \qquad (1)$$

where F is specific gravity, C is the weight of the sample (g), and E is the weight of the water (g) computed by E = D - B, where D is the combined weight of the flask, sample, and water (g) and B is the combined weight of the sample and flask (g).

Two (2) specimens were examined for each material to produce an average value, as shown in Table 1

Table 1. Specific gravity of FNS

Experiment		Unit	FNS (Test 1)	FNS (Test 2)
Flask Weight	(A)	g	224	224
Sample and Flask Weight	(B)	g	724	724
Sample Weight	(C = B-A)	g	500	500
Flask, Sample, and Water Weight	(D)	g	1055	1055.8
Water weight	(E = D-B)	g	331	311.8
Specific Gravity	(F = C/(C-E)	g	2.958	2.972
Average			2.9656	

The bulk density of fine nickel slag was evaluated in accordance with ASTM C29/C29M [22] by a standard test method. The empty container was weighed first and then filled to the full with fine nickel slag and weighed to get the final measurement (Table 2). The bulk density may be calculated from the obtained weights according to equation (2):

$$E = \frac{D}{A} \quad (2)$$

where E is the bulk density (g/cm³), D is the weight of the sample (g), computed as D=C-B, where C is the weight of the sample and container together (g), and B is the weight of the empty container (g), and A is the capacity of the container (cm³).

Table 2 shows the average value obtained from testing two (2) specimens.

Table 2. Results of the bulk density test of FNS

Experiment		FNS (Test 1)	FNS (Test 2)
Container Volume	(A)	2002	2002
Container Weight	(B)	774	774
Sample and Container Weight	(C)	4743.4	4746.4
Sample Weight	(D= C-B)	3969.4	3972.4
Bulk Weight	(E = D/A)	1.982	1.984
Average		1.983	

3.3 Capacity for water absorption

The Water Absorption Capacity test is shown in Table 3. The water absorption test is important for civil engineering to find out the quantity of water that a material, usually aggregate, can absorb. In this test, the aggregate is oven-dried to eliminate all moisture and then weighed. The sample is then immersed in water for 24 hours to achieve complete saturation. The material is weighed again in SSD condition after removing the surface moisture. Water absorption % is calculated as the difference between dry and SSD weights according to ASTM C128 [21] using equation (3):

$$E = \frac{C - D}{D} \times 100 \quad (3)$$

where E is the water absorption capacity (%), C is the weight of the sample before drying (g), and D is the weight of the sample after oven drying (g).

This test is used to find out the porosity and water holding capacity of the aggregate, which affects the workability, durability, and strength of concrete. Mix designs may require changes with high water absorption aggregates to guarantee optimal hydration and performance. Two (2) specimens were evaluated to get an average result as shown in Table 3.

Table 3. Results of water absorption of FNS

Experiment		Unit	FNS (Test 1)	FNS (Test 2)
Pan Weight	(A)	g	654	654
Sample and Pan Weight	(B)	g	1654	1654
Sample Weight	(C = B-A)	g	1000	1000
Dry Sample Weight	(D)	g	991.2	991.6
Water Absorption Capacity	(E = C-D/D)	g	0.888	0.847
Average		%	0.867	

3.4 Moisture content

The Moisture Content test is an important test in civil engineering that determines the quantity of water in materials such as soil or aggregate. For this study, the procedure followed ASTM C566 [23]. A Sample is weighed first while still wet, then placed in the oven and dried at a set temperature until its weight no longer changes. From these two readings, the moisture content is worked out as a percentage of the dry weight, following equation (4):

$$MC = \frac{Wwet - Wdry}{Wdry} \times 100 \quad (4)$$

where MC is the moisture content (%), Wwet is the weight of the wet sample (g), and Wdry is the weight of the oven-dried sample (g).

This test is crucial since the moisture content impacts the behaviour of the material, especially its compaction, strength, and stability in building projects. Controlling moisture is vital to the performance of materials like concrete, soil, and asphalt in different building uses.

3.5 Gold Tailings

To properly substitute cement with gold tailing, GT should be as near as feasible to the cement composition, which is CaO, SiO_2, and Al_2O_3. The key components of Portland Cement are as follows. The industrial statistics on the main components of gold tailings show that GT is quite comparable to cement, at least in terms of practicality for the research (Table 4) [25]. Furthermore, the material must conform to certain standards about human safety, for example, the restrictions on the amount of parts with lead [26]. Here comes the analytical report of Gold Tailing (GT).

Table 4. Cement, Gold Tailing (GT), and Fine Nickel Slag (FNS) compounds

Compounds	OPC [24]	GT (%)	FNS (%)
CaO	63.2	13.54	24.71
SiO_2	18.45	15.50	41.24
Al_2O_3	4.96	3-8	9.69
Fe_2O_3	2.86	2-4	1.71
MgO	3.52	1-5	19.29
Na_2O+K_2O	0.31	1-3	0.41
SO_3	2.18	0.3-1.5	0.9

Table 5. GT and FNS Elements of Toxicity Leaching Procedure Test (TCLP)

Elements	Limit the US EPA	GT	FNS
	[mg/L]	[mg/L]	[mg/L]
Arsenic	5	0,01	0.5
Barium	100	0.09	35
Cadmium	1	0.09	0.15
Chromium	5	0.08	2.5
Lead	5	7.9	0.5
Mercury	0,2	0.01	0.05
Selenium	1	0.01	0.5
Silver	5	0.01	5

Lead content in the gold tailings has been reported to be higher than the USEPA regulation limit, and is therefore, a possible health and environmental hazard (Table 5). It should be noted that this TCLP result is for the raw gold tailings material before encapsulation in the cement matrix. Once bound in hardened concrete, heavy-metal leachability is generally lower due to the alkaline pore environment and physical confinement.

Fig. 1 Results of the packing density test of GT5 [28]

This mitigating effect has not been directly verified in the present study by TCLP testing of the hardened concrete itself. Hence, the use of GT-substituted concrete for in-field application is not advisable at this stage due to the high lead concentration in the raw material unless additional TCLP verification is performed on the hardened concrete and, if necessary, an appropriate stabilization treatment is utilized to maintain leachability below the USEPA limit [26]. The optimal water to cement ratio was determined to be higher than that of OPC as GT absorbs more water than OPC [12][27] (Fig. 1).

3.6 Concrete Mix Design and Documentation

Now, in Figure 2, real images are provided depicting the entire experimental technique, from raw material preparation to physical property testing, concrete mixing and casting, and mechanical and durability testing. Two (2) specimens per material were subjected to aggregate characterisation tests (specific gravity, bulk density, and water absorption) to get an average result. For each of the concrete mixtures (Ref, GT5, GT10, GT15, GT20, and GT25), three (3) specimens were prepared per batch for each of the mechanical and durability test parameters (compressive strength, splitting tensile strength, porosity, and gas permeability) as per the standard practice of testing replicates to guarantee the reliability of the results.

Mix design based on the absolute volume method as per ACI 211.4R for high-strength concrete. The reference mixture (Ref) was constructed of 488.10 kg/m³ cement, a water/cement ratio of 0.42, 770.9 kg/m³ natural sand, and 881.0 kg/m³ gravel, and a polycarboxylate superplasticizer at 1% of binder weight to provide workability at this low w/c ratio. The cement was replaced by gold tailings (GT) and natural sand by fine nickel slag (FNS) at equal weight basis and simultaneously at the same percentage, in the range of 5% to 25% (GT5 – GT25). For example, in mixture GT5, the cement mass is replaced by 5% of GT, and simultaneously, the sand mass is replaced by 5% of FNS. For all combinations, the binder concentration, w/c ratio, superplasticizer dosage, and the amount of gravel were maintained constant. The ratios of cement-GT and sand-FNS were changed only with the replacement level. The fine aggregate content was rectified volumetrically for the varied specific gravities of GT (2.56), FNS (2.96), cement (3.155) and sand (2.53). The total volume of each combination was 1 m3 with a 2% presumed entrapped air. Total batch quantities are shown in Table 6.

Fig. 2 Experimental Documentation (Preparation materials, Physical property testing, Concrete mixing, and Mechanical and durability testing)

Table 6. Mix Design of the tested concrete (in kg/m^3)

Concrete Mixture	Binders		Fine Aggregates		Coarse aggregate	Water	SP	w/c ratio
	OPC	GT	Natural	FNS				
Ref	488.10	0	764.90	0	881	205	4.881	0.42
GT5	463.69	24.41	727.62	38.30	881	205	4.881	0.42
GT10	439.29	48.81	690.25	76.69	881	205	4.881	0.42
GT15	414.88	73.22	652.79	115.20	881	205	4.881	0.42
GT20	390.48	97.62	615.24	153.81	881	205	4.881	0.42
GT25	366.08	122.03	577.59	192.53	881	205	4.881	0.42

4. RESULTS AND DISCUSSIONS

4.1 Workability

Material testing findings of concrete binders produced specific gravities of 3.155 for OPC and 2.56 for GT cement correspondingly. The material testing findings of concrete ingredients included specific gravity, moisture content and absorption. The findings of specific gravity of Fine aggregates, coarse aggregates and Fine nickel slag (FNS) were found to be 2.53, 2.54 and 2.96 accordingly. The values of water content and coarse aggregate were 2.53% and 0.78% respectively. Coarse aggregate absorption 2.86, 2.81. Fine aggregate The European Federation for specialized construction chemicals and concrete systems (EFNARC) [29]. Testing for workability.

The results of workability are shown in Figure 3, where the slump value was further reduced with increasing the replacement percentage of gold tailing (GT) and fine nickel slag (FNS) from 5% to 25%. The control mixture showed the largest droop value while the workability was minimum for the GT25 combination. The reduction in slump is largely due to the higher water absorption capacity and different particle texture of GT and FNS compared to regular cement and natural sand. The higher the replacement percentage, the more mixing water was used by the substituted elements. This decreased the amount of free water present in the concrete mix, resulting in a stiffer consistency. Moreover, the roughness and angularity of the FNS increased the internal friction between particles, which led to a decrease in flowability. These results are consistent with prior studies, which have revealed that industrial waste materials with strong absorption properties impact the workability and slump performance of concrete [8][9][27].

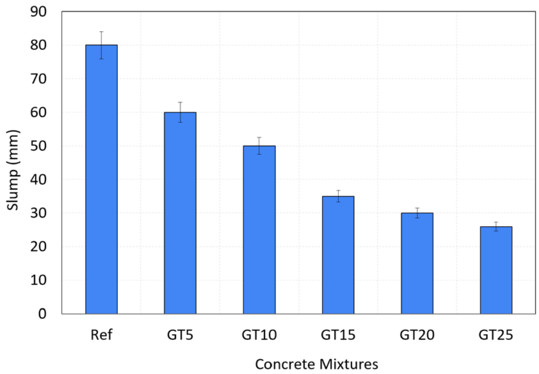

Fig.3 Workability of Concrete with GT and FNS Replacements

4.2 Concrete Compression Test

The compressive strength test was performed according to ASTM C39/C39M [30] on three (3) cylindrical specimens per batch for each concrete mixture. The compressive strength was computed as per equation (5):

$$f'c = \frac{P}{A} \quad (5)$$

where f'c is the compressive strength (MPa), P is the maximum applied load (N), and A is the cross-sectional area of the cylindrical specimen (mm^2).

As demonstrated in Figure 4 and Table 7, the compressive strength gradually decreased with the rise in the combined GT-FNS substitution level, from 42.27 MPa in the reference combination to 23.55 MPa at 25% replacement. It seems that the two materials are working through different paths that end up reinforcing one another. With GT used in place of cement, the available binder thinned out, and since more water is demanded by it, the intended water-to-cement ratio is thrown off. With FNS used in place of sand, a rougher and more angular surface is brought in, and by this, the bond between the aggregate and the paste is weakened. When these effects are put together, hydration is made less efficient, and the matrix is left more porous, so in the end, the compressive strength is brought down. Even so, only a minimum strength of 21 MPa is asked of Indonesian residential concrete, and this limit was passed comfortably by every mix, GT25 included, so it can be said that GT and FNS are still dependable as structural substitutes across the whole range that was tested [13][17].

Table 7. Compressive and tensile strength results at 28 days

Concrete Variations	Compressive Strength (MPa)	Tensile Strength (MPa)
Ref (OPC)	42.27	14.90
GT5	38.03	14.26
GT10	36.63	12.35
GT15	31.02	11.33
GT20	24.66	10.53
GT25	23.55	8.79

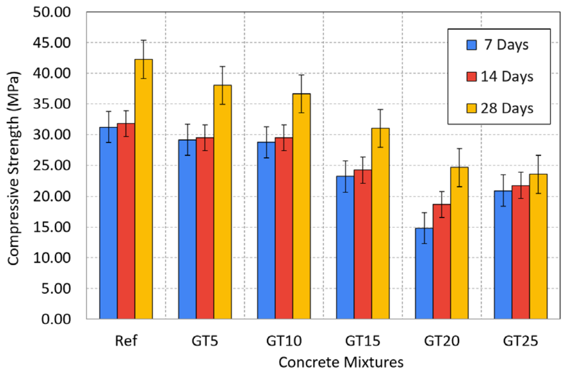

Fig.4 Concrete compressive strength

The splitting tensile strength test was conducted as per ASTM C496/C496M [31] on three (3) cylindrical specimens for each batch per concrete mixture. The splitting tensile strength was computed as per equation (6):

$$ft = \frac{2P}{\pi LD} \quad (6)$$

where ft is the splitting tensile strength (MPa); P is the maximum applied load (N); L is the length of the specimen (mm), and D is the diameter of the specimen (mm).

Similarly to the compressive strength, the tensile strength also decreased with the increase in the substitution level of gold tailings (GT) and fine nickel slag (FNS), where the reference mixture (Ref) achieved the highest tensile strength of 14.90 MPa, and GT25 obtained the lowest value of 8.79 MPa, reflecting the same FNS-induced bond weakening and GT-induced hydration disruption as observed for compressive strength. It is noteworthy that the tensile to compressive strength ratio obtained (approx. 35% for the reference mixture) is higher than the typical 8-12% reported for normal weight concrete; while this may partly be due to the specific geometry of the specimens and curing conditions used in this experimental programme, it is a finding that deserves further validation in subsequent testing campaigns. However, even at modest substitution levels, tensile strength performance was commensurate with sustainable concrete applications documented in the literature [9][32] despite the decrease with substitution.

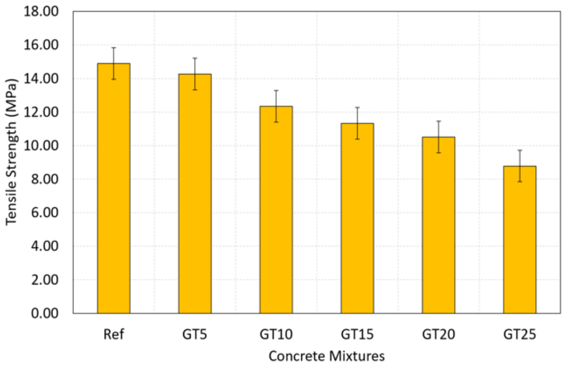

Fig.5 Tensile Strength Results

4.3 Porosity Test

Porosity in concrete is a major indication of its internal structure and durability. It immediately affects the permeability, mechanical characteristics, and environmental resilience of the material. In this work, the porosity test was carried out in accordance with ASTM C642 [33] to determine the effect of fine nickel slag (FNS) and gold tailings (GT) as partial replacements for cement and sand on the pore structure of concrete. Three (3) concrete specimens per batch were cured for 28 days to evaluate total porosity. The concrete specimens were then oven-dried at 105°C for 24 hours to eliminate free moisture. The dried samples were weighed (dry weight, Wd) and then soaked in water for 24 h. The specimens were weighed in the saturated surface-dry state (SSD weight, Wssd) and in the totally submerged condition (submerged weight, Wsub) after immersion. The porosity (ϕ) was determined using the following equation (7):

$$ø\ (\%) = \frac{\boldsymbol{Wssd - Wd}}{\boldsymbol{Wssd - Wsub}} \times \mathbf{100} \qquad (7)$$

This test was carried out on all of the concrete mixes, the control (Ref) as well as the GT5-GT25 variants. The results are presented in Fig. 6, and Table 8, and a gradual rise in porosity is shown as the GT and FNS substitution levels are increased. The lowest porosity was recorded for the control sample, which had a denser matrix, whereas the greatest porosity was found in GT25. Here, too, the two materials appear to be acting through different pathways. Because of GT’s higher water demand, extra capillary pores are left behind as the surplus water is evaporated during curing, while because of FNS's irregular, angular particle shape, compaction is disrupted and more voids are created at the paste-aggregate interface.

The increase in porosity that was observed is in line with the earlier work of Chen et al. [8] and Juenger et al. [17], by whom it was found that the void content can be raised when industrial by-products are over-substituted, owing to less-than-ideal particle packing and a higher uptake of internal moisture. However, the lowest porosity was recorded for the control sample, which had a denser matrix, whereas on of GT5 showed an acceptable porosity, fulfilling the standards of structural-grade concrete, while presenting advantages in terms of sustainable material.

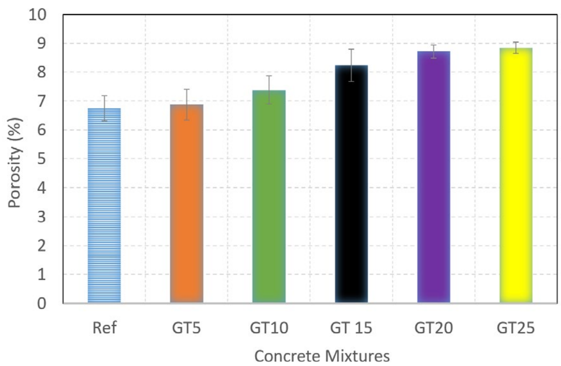

Fig.6 Porosity Test Results

Table 8. Porosity test results of concrete at 28 days

Concrete Variations	Porosity (%)
Ref (OPC)	6.746
GT5	6.871
GT10	7.382
GT15	8.237
GT20	8.718
GT25	8.845

4.4 Permeability Test

The permeability test is very important for the assessment of the durability of concrete, especially when using alternative materials such as fine nickel slag (FNS) and gold tailings (GT). If a concrete has a high gas permeability, this is an indication that there is a well-linked pore network. Water, chlorides, and other aggressive agents can permeate via this network, and this will ultimately lead to an accelerated degradation of reinforced concrete buildings. The test was performed to assess the effect of adding FNS and GT on the gas permeability of concrete, using the RILEM-CEMBUREAU technique specified by RILEM TC 116-PCD [34]. Three (3) cylinder concrete specimens (150 mm diameter x 50 mm height) were produced for each mix variation, comprising control (OPC) and replacement levels of 5%, 10%, 15%, 20%, and 25%. After 28 days of water curing, the specimens were oven-dried to constant mass and sealed in the permeability cell. Oxygen gas was delivered at the unflet face at five absolute pressure levels (150, 200, 250, 300, and 350 kPa) and the steady state volumetric flow rate at the exit, at atmospheric pressure (101.325 kPa), was measured at each pressure level. The apparent gas permeability coefficient was estimated from the observed flow rate according to equation (8):

$$K = \frac{2QPo\mu L}{A(P^2 - Po^2)} \quad (8)$$

Where K is the apparent gas permeability coefficient (m2), Q is the measured outlet gas flow rate (m3 /s), P0 is the atmospheric (outlet) abolute pressure (Pa), and μ is the dynamic viscosity of oxygen (2.02 x 10-5 Pa.s), L is the specimen height (m), A is the across sectional area of the speciment (m2), and P is the applied inlet absolute pressure (Pa). The stated coefficient for each combination is the mean of the K values obtained at the five pressure levels.

From Figure 7 and Table 9, it can be shown that the gas permeability coefficient rose continuously with substitution, from 1.093×10^{-15} m² in the reference mixture to 2.008×10^{-15} m² at 25% replacement, which is almost double the control value. Similar to porosity, GT and FNS appear to be responsible for this increase by complementary mechanisms: GT's higher water absorption leaves residual capillary channels behind once excess water evaporates during curing, while FNS's irregular particle morphology is less effective at disrupting pore continuity compared to well-graded natural sand, and the two create a more interconnected pore network, which facilitates gas migration. However, even significant replacement levels still provided good durability performance for non-aggressive exposure circumstances.

These results are in agreement with Han et al. [4] and Nuruzzaman et al. [9], who found higher permeability of concrete mixes including industrial waste due to microstructural alterations and higher porosity. However, modest degrees of replacement (up to 15%) still showed adequate performance. Wang et al. [13] further strengthen this by highlighting the significance of adjusting the mix design to achieve a balance of sustainability and durability in high-performance concrete with tailings and slags.

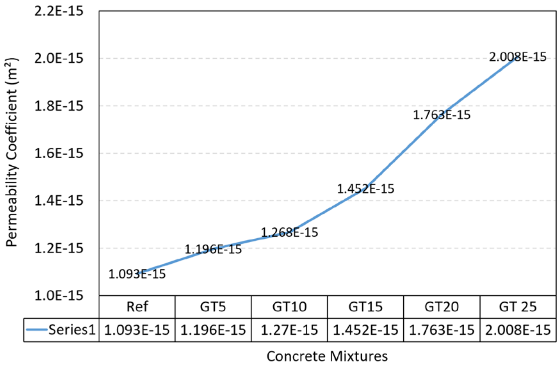

Fig.7 Results of Gas Permeability Test of Concrete with GT and FNS Replacements

Table 9. Gas permeability coefficient results at 28th day

Concrete Variations	Permeability Coefficient (m²)
Ref (OPC)	1.093×10^{-15}
GT5	1.196×10^{-15}
GT10	1.268×10^{-15}
GT15	1.452×10^{-15}
GT20	1.763×10^{-15}
GT25	2.008×10^{-15}

5. CONCLUSION

In this work, fine nickel slag (FNS) and gold tailings (GT) were utilized to partially replace cement and sand in concrete to provide a more sustainable building material. The results showed that the workability and strength decreased with increasing substitution levels, but the mixture with 5% FNS and GT (GT5) had the best performance among all substitution mixtures, with a compressive strength of 38.03 MPa after 28 days, which was significantly above the standard strength used in Indonesian residential construction. Tensile strength decreased a little in all the mixes.

The results of this study indicate that industrial waste materials such as nickel slag and gold tailings may be reutilized in the manufacturing of concrete without any adverse effect on quality if used at optimum quantities. This reduces demand for natural resources and provides an environmentally friendly solution to handle mining waste. This research helps to the development of greener and more circular building processes by converting garbage into a valuable construction input.

However, the high lead content found in the raw gold tailings prevents recommending field deployment of GT, replaced concrete without additional testing. In future work, attention should be directed toward TCLP testing of the hardened concrete itself rather than of the raw material itself, and the long-term leaching behavior together with the durability under real field-exposure conditions should be assessed before these mixes are considered for practical use.

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7. REFERENCES

1. Sunarno A.R.Y., Rangan P. R., Ampangallo B. A., Aryadi A., Oksri-Nelfia L, Rinanti A., The Influence of Chemical Admixture Types on the Mechanical Properties of Concrete with 100% Fly Ash Substitution, International Journal of GEOMATE, Vol 28, Issue 129, 2025, pp. 138–145 https://doi.org/10.21660/2025.129.g14383
2. Zhao H., Sun W., Wu X., and Gao B., "The properties of the self-compacting concrete with fly ash and ground granulated blast furnace slag mineral admixtures," J. Clean. Prod., vol. 95, 2015, pp. 66–74 https://doi.org/10.1016/j.jclepro.2015.02.050
3. Oksri-Nelfia L. et al., "Comprehensive Characteristics of High-Performance Concrete with Nickel Slag as Fine and Coarse Aggregate," Int. J. Technol., vol. 15, no. 6, 2024, pp. 1613–1631 https://doi.org/10.14716/ijtech.v15i6.7184
4. Han F., Zhang H., Li Y., and Zhang Z., Recycling and comprehensive utilization of ferronickel slag in concrete, J. Clean. Prod., vol. 414, 2023, pp. 13763 https://doi.org/10.1016/j.jclepro.2023.137633
5. Permatasari I. W., Oksri-Nelfia L., Siregar P. H. R., and Yuwono B. E., "A literature review on the durability of ferrous and non-ferrous geopolymer concrete for sustainable developments," IOP Conf. Ser. Earth Environ. Sci., vol. 780, 2020, pp. 01206 https://iopscience.iop.org/article/10.1088/1755-1315/780/1/012006
6. Song Q., Zou Y., Bao J., and Zhang P., "Disposal of solid waste as building materials: A study on the mechanical and durability performance of concrete composed of gold tailings," J. Mater. Res. Technol., vol. 30, 2024, pp. 2111–2124 https://doi.org/10.1016/j.jmrt.2024.03.191
7. Ince C., "Reusing gold-mine tailings in cement mortars: Mechanical properties and socio-economic developments for the Lefke-Xeros area of Cyprus," J. Clean. Prod., vol. 238, 2019, pp. 117871 https://doi.org/10.1016/j.jclepro.2019.117871
8. Chen S. C., Wang M. T., Gu L. S., Lin W. T., Liang J. F., and Korniejenko K., "Effects of incorporating large quantities of nickel slag with various particle sizes on the strength and pore structure of cement-based materials," Constr. Build. Mater., vol. 393, 2023, pp. 132034 https://doi.org/10.1016/j.conbuildmat.2023.132034
9. Nuruzzaman N., Casimiro J. O. C., and Sarker P. K, "Fresh and hardened properties of high-strength self-compacting concrete using by-product ferronickel slag fine aggregate," J. Build. Eng., vol. 32, Issue. 2020, pp 101686 https://doi.org/10.1016/j.jobe.2020.101686
10. S. Li, J. Chen, W. Gao, X. Lyu, Z. Liang, and W. Zhou, "Current situation and prospects for the clean utilization of gold tailings," Waste Manag., vol. 180, 2024, pp. 149–161 https://www.sciencedirect.com/science/article/abs/pii/S0956053X24001867
11. Ma Y., Zhang B., Lin Y., Huang Y., Zheng D., and Ji T., "Effect of nickel slag on the basic tensile creep of alkali-activated slag/nickel slag mortars," Constr. Build. Mater., vol. 351, 2022, pp. 128778 https://doi.org/10.1016/j.conbuildmat.2022.128778
12. Dey A. et al., "Towards net-zero emission: A case study investigating sustainability potential of geopolymer concrete with recycled glass powder and gold mine tailings," J. Build. Eng., vol. 86, 2024, pp. 108683 https://doi.org/10.1016/j.jobe.2024.108683
13. Wang J. N. et al., "A novel design of low carbon footprint Ultra-High Performance Concrete (UHPC) based on full scale recycling of gold tailings," Constr. Build. Mater., vol. 304, 2021, pp. 124664 https://doi.org/10.1016/j.conbuildmat.2021.124664
14. Bouaissi A., Li L. Y., Abdullah M. M. A. B., and Bui Q. B., "Mechanical properties and microstructure analysis of FA-GGBS-HMNS-based geopolymer concrete," Constr. Build. Mater., vol. 210, 2019, pp. 198–209 https://doi.org/10.1016/j.conbuildmat.2019.03.202
15. Zhong H. et al., "Compressive Behaviors of High-Strength Geopolymeric Concretes: The Role of

Recycled Fine Aggregate," Buildings, vol. 14, no. 4, 2024, pp. 1–22 https://doi.org/10.3390/buildings14041097
16. Wang G. C., A Book: The utilization of slag in civil infrastructure construction, Elsevier Publisher, 2016, pp 1–405 https://doi.org/10.1016/C2014-0-03995-0
17. Juenger M. C. G., Snellings R., and Bernal S. A., "Supplementary cementitious materials : New sources, characterization, and performance insights," Cem. Concr. Res., vol. 122, 2019, pp. 257–273 https://doi.org/10.1016/j.cemconres.2019.05.008
18. ACI 211.4R-93, "Guide for Selecting Proportions for High-Strength Concrete with Portland Cement and Fly Ash," vol. 93, 1998 no. Reapproved
19. American Standard Testing and Material (ASTM) C143M-15, Standard Test Method for Slump of Hydraulic-Cement Concrete.
20. ASTM C136/C136M-19, Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates, ASTM International, West Conshohocken, PA, 2019.
21. ASTM C128-22, Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate, ASTM International, West Conshohocken, PA, 2022.
22. ASTM C29/C29M-17a, Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate, ASTM International, West Conshohocken, PA, 2017.
23. ASTM C566-19, Standard Test Method for Total Evaporable Moisture Content of Aggregate by Drying, ASTM International, West Conshohocken, PA, 2019.
24. Oksri-Nelfia L., Raditya A., Triastuti, A. Nugroho, Syamsunur D., and Amiri O., "Sago Palm Fibers and GGBFS for Sustainable High-Tensile-Strength Self-Compacting Concrete," Int. J. GEOMATE, vol. 28, Issue. 125, 2025, pp. 44–55 https://geomatejournal.com/geomate/article/view/4650
25. Wang Q., Yao G., Zhu X., Wang J., Wu P., and Lyu X., "Preparation of Portland Cement with Gold Ore Tailings," Adv. Mater. Sci. Eng., vol. 351, 2019, pp. 128778 https://doi.org/10.1155/2019/1324065
26. Apithanyasai S., Supakata N., and Papong S., "The potential of industrial waste: using foundry sand with fly ash and electric arc furnace slag for geopolymer brick production," Heliyon, vol. 6, Issue 3, 2020, pp. 03697 https://doi.org/10.1016/j.heliyon.2020.e03697
27. Wang Q. et al., "Approach to the management of gold ore tailings via its application in cement production," J. Clean. Prod., vol. 269, 2020, pp 122303 https://doi.org/10.1016/j.jclepro.2020.122303
28. Oksri-Nelfia L., Mahieux P. Y., "Reuse of recycled crushed concrete fines as mineral addition in cementitious materials," Materials and Structures, 2015, pp. 1-13 https://doi.org/10.1617/s11527-015-0716-1
29. EFNARC, "Specification and Guidelines for Self-Compacting Concrete," vol. 44, 2002.
30. ASTM C39/C39M-21, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, ASTM International, West Conshohocken, PA, 2021.
31. ASTM C496/C496M-17, Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens, ASTM International, West Conshohocken, PA, 2017.
32. Edwin R.S., Ngii E., Talanipa R., Masud F., and Sriyani R., "Effect of nickel slag as a sand replacement in strength and workability of concrete," IOP Conf. Ser. Mater. Sci. Eng., vol. 615, Issue 1, 2019, pp. 1-6 https://iopscience.iop.org/article/10.1088/1757-899X/615/1/012014/meta
33. ASTM C642-21, Standard Test Method for Density, Absorption, and Voids in Hardened Concrete, ASTM International, West Conshohocken, PA, 2021.
34. RILEM TC 116-PCD, Test for gas permeability of concrete. B: Measurement of the gas permeability of concrete by the RILEM CEMBUREAU method, Mater. Struct., vol.32, 1999, pp 176-178. https://doi.org/10.1007/BF02481511