An Investigation of the Characteristics and Microstructure of Gold Tailing Powder Utilized as a Cement Substitute

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ABSTRACT

This research studied the feasibility of using tailings waste from gold mining as a partial replacement for cement in standard concrete mixes. Its objective was to determine whether the addition of tailings waste could meet or exceed the specifications of standard concrete. Another goal of this study was to provide solutions for the utilization of waste that will benefit the environment and the economy. The tailings substitutions used in this study were 5%, 10%, 15%, 20%, and 25% of the mix. Their content is similar to that of cement, including Fe_2O_3 = 8.52%, Al_2O_3 = 15.50%, and SiO_2 = 49.01%. The slump value of standard concrete was 80 mm and that of concrete with 25% tailings substitution was 55 mm. Ordinary concrete has a compressive strength between 20 MPa and 40 MPa. The strength of concrete mixes reduced as the proportion of tailings waste rose, according to tests conducted 28 days after the concrete had aged. The mix with 10% substitution had the best performance with a compressive strength of 53.32 MPa and a tensile strength of 3.61 MPa. Although the tailings contain similar compounds to cement, it was shown that when the amount of tailings that substituted cement in concrete mixes was increased, decreasing values were observed for workability, compressive strength, and tensile strength. Nevertheless, these decreases still meet the standard specifications proving that tailings waste can substitute cement in concrete mixes and produce an environmentally friendly concrete.

Keywords-green concrete; gold tailings; substitution cement; workability

I. INTRODUCTION

The mining sector generates high waste, such as tailings, waste rock, and hazardous materials [1, 2]. Indonesia is the eighth-largest gold producer in the world but generates liquid and gaseous waste, including acid mine drainage, heavy metals, dust, and greenhouse gas emissions [3, 8].

The construction industry supports the world's economy but faces significant challenges in terms of reducing the environmental impacts from the cement production, which creates carbon emissions [9]. The extraction of non-renewable resources, such as sand, also damages the ecosystems [10]. As a solution, the construction industry is adopting sustainable practices by using substitute materials from industrial waste [11].

It has been shown that the cement production reduces the non-renewable resources and damages the environment [12]. Tailings that contain compounds, such as silica (SiO_2) and calcium oxide (CaO), have the potential to be used as building materials [13]. Concrete with 5% tailings and 10% glass chips had a compressive strength of 32.35 MPa after 28 days of age, while concrete with a tailings mixture for cement replacement had a compressive strength of less than 20 MPa [14]. Although tailings can be used in the construction industry, it is vital to check whether their composition includes hazardous waste [15]. It has been demonstrated that coal mine tailings can be utilized as building materials and support a circular economy that provides both environmental and economic benefits [16].

This study investigates the feasibility of utilizing tailings from gold mining waste as a substitute for cement in concrete. It examined their chemical and mineralogical properties, taking into account the environmental sustainability and circular economy concepts. The aim of this research is to optimize the concrete formulation in order to satisfy the structural strength standards and therefore produce alternative construction materials from gold mining waste.

II. RESEARCH METHODOLOGY

A. *Material*

The concrete mix design in this study, used Ordinary Portland Cement (OPC) type 1 cement from Tiga Roda as the main binder. The fine aggregate was from Quarry sand in Bogor, while the coarse aggregate was from Holcim crushed stone in Bogor. The water used had to be clean to support cement hydration. Viscocrete 3115n superplasticizer was added at 0.2% to improve the concrete performance. The Gold Tailings (GT) that were used as a partial cement replacement were obtained from PT Djoyoline Indonesia. The particle size analysis of the GT powder was conducted deploying a standard sieve method. The results showed that the tailing sample passed through sieve No. 200, indicating that the particle size was finer than 75 microns.

Although detailed gradation curves are not available, this fineness suggests that the tailings are within the suitable range for use as a supplementary material for cement. The OPC for example, has a similar or slightly finer particle size distribution, which confirms the compatibility of the tailings for partial cement replacement in concrete mixtures.

Fig. 1. Sample of GT.

B. *Mix Design*

The design of the concrete mix was prepared in 6 variations: Ref, GT5, GT10, GT15, GT20, and GT25. The Ref mix used 100% OPC cement as the binder. The other variations were concretes with cement substitution from GT waste of 5%, 10%, 15%, 20%, and 25%, respectively.

All mixes used fine aggregate (sand), coarse aggregate (gravel), water, and superplasticizer at 0.2% of the total weight of the binder. The concrete samples were made using a cylindrical mold with a diameter of 15 cm and a height of 30 cm.

TABLE I. MIX DESIGN OF THE STUDIED CONCRETE

Materials	Ref (kg/m^3)	GT (kg/m^3)				
		5%	10%	15%	20%	25%
OPC	488	464	439	415	390	366
GT	0	24	49	73	98	122
Coarse aggregate	881	881	881	881	881	881
Fine aggregate	771	693	691	689	687	685
Water	205	205	205	205	205	205
W/(C+GT)	0.42	0.42	0.42	0.42	0.42	0.42
Superplasticizer	0.98	0.98	0.98	0.98	0.98	0.98

C. *Experiment*

The experiment consisted of 3 stages:

- Assessment of tailings characterization.
- Manufacture of tailings concrete specimens according to the percentages presented in Table I.
- Evaluation of workability, durability, and characterization of tailings concrete.

The X-ray Fluorescence (XRF) testing utilized an Epsilon 5 device to analyze the chemical element composition, while the Toxicity Characteristic Leaching Procedure (TCLP) confirmed the absence of heavy metal contamination in the concrete.

The compressive strength of the cylinder samples was evaluated using a 2000 kN digital compression machine after 28 days. The concrete's shear resistance was assessed by testing its tensile strength. The permeability of the concrete was determined by applying gas pressure to the concrete samples. The porosity was calculated based on the weight of the samples in both dry and water-soaked conditions. Fourier Transform Infrared (FTIR) Spectroscopy was performed using a Nicolet IS5 machine to analyze the chemical structure of the concrete. X-ray Diffraction (XRD) was conducted with a Bruker machine to identify the crystalline phase and structure. Finally, Scanning Electron Microscopy (SEM) with a Jeol JSM-IT200 was employed to examine the microstructure and chemical composition of the concrete. These tests were carried out on standard concrete (Ref), concrete with 10% GT10, and concrete with 25% GT (GT25) after 28 days, to ensure the quality and safety of the concrete that was made from GT.

III. RESULTS AND DISCUSSION

A. X-Ray Fluorescence

The XRF test results of GT showed that their main contents were Fe_2O_3 (8.52%), Al_2O_3 (15.50%), and SiO_2 (49.01%). This is similar to the composition of pozzolanic cement [17, 18]. Table II displays the composition of OPC and GT [19].

TABLE II. MATERIAL COMPOSITION TEST TABLE

Parameter	OPC (%)	GT (%)
Calcium Oxide (CaO)	63.20	13.34
Aluminum Trioxide (Al_2O_3)	4.96	15.50
Silicon Dioxide (SiO_2)	18.45	49.01
Iron Trioxide (Fe_2O_3)	2.86	8.52
Magnesium Oxide (MgO)	3.52	1.86
Potassium Oxide (K_2O)	0.31	0.54
Sodium Oxide (Na_2O)	0.15	1.83
Loss on Ignition (LOI)	3.42	8.23
Titanium Dioxide (TiO_2)	-	0.77
Moisture Content (MC)	-	4.96

B. Slump Test (Workability)

The fresh concrete testing was carried out by testing the slump using an Abrams cone tool under standard conditions [20]. Figure 2 shows that Ref concrete had the highest slump value of 80 mm, followed by GT5 (70 mm), GT20 (60 mm), GT10 (58 mm), and GT25 (55 mm).

This indicates a decrease in workability with the addition of tailings. These results comply with those of [21]. It is proposed to substitute no more than 30% of the tailings in concrete.

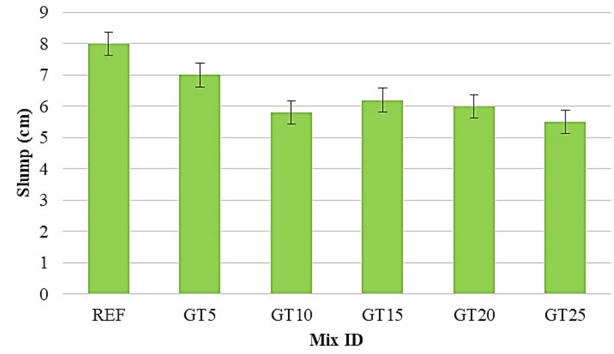


Fig. 2. Results of the slump test conducted using an Abrams cone apparatus under standard conditions.

C. Compressive Strength of Concrete

The compressive strength tests conducted on concrete after 7, 14, and 28 days, revealed a decline in all mixes [22]. The GT25 had the most significant loss (44%) and GT10 had the least (13%).

Figure 3 exhibits that at each test age, Ref concrete had the best compressive strength, whereas GT concrete fluctuated. At 28 days, Ref concrete reached 60.39 MPa, while GT25 only 33.65 MPa. In general, GT concrete exceeded the standard of 30 MPa at 28 days. Specifically, the GT10 concrete had the highest compressive strength among the GT mixes, showing the pozzolanic effect at 10% tailings [23, 24]

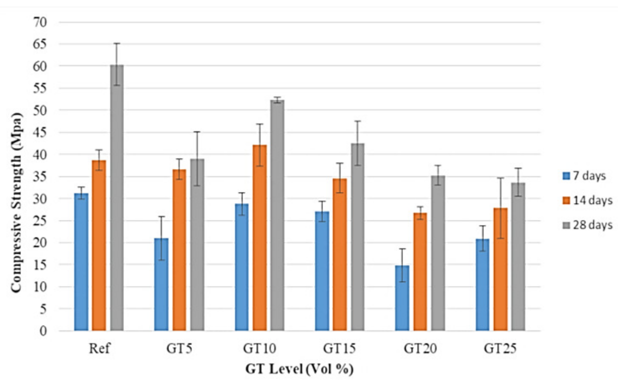


Fig. 3. Effect of GT on the compressive strength of concrete.

D. Tensile Strength of Concrete

The tensile strength test is calculated based on [25]. The results, as illustrated in Figure 4, showed that the Ref concrete had the highest tensile strength (3.73 MPa), while the tensile strength of all concretes with tailings decreased. The GT20 had the lowest value (2.20 MPa) and GT10 the highest (3.61 MPa). This confirms the fact that the replacement of cement with tailings reduces the tensile strength of concrete [26, 27].

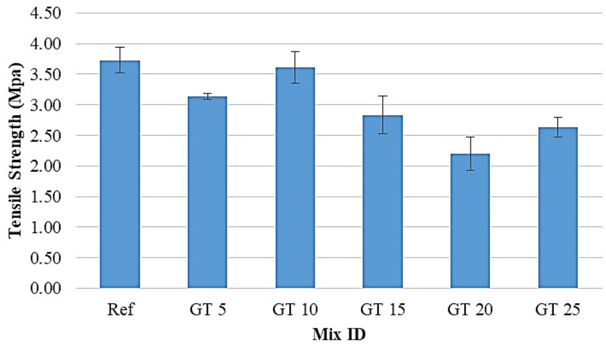


Fig. 4. Tensile strength results (at 28 days) after testing with a digital concrete compression machine.

E. Porosity of Concrete

The concrete porosity testing can be calculated as shown in [28]. Figure 5 demonstrates the increase in the porosity of concrete with the addition of GT. The GT25 concrete (25% tailings) exhibits the highest porosity of 9.729%, while the Ref concrete has a porosity of 8.237%. This indicates that there are more voids in GT25 concrete than in standard concrete, which is in line with studies showing that more than 15% tailing substitution increases the voids in 28-day-old concretes [29, 30].

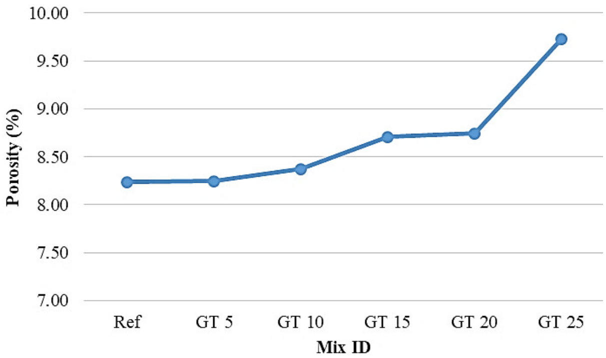


Fig. 5. The results of the porosity of concrete.

F. Permeability Of Concrete

The permeability tests (at 28 days of concrete age) were conducted using specimens of 150 mm diameter, 50 mm height, and a varying water pressure from 0.15 N/mm² to 0.35 N/mm² for 20 sec [31].

As illustrated in Figure 6, the highest permeability coefficient was found in GT25 concrete (2.28156×10^{-6}), while the lowest was found in Ref concrete (1.09259×10^{-6}). These results indicate that the more tailings there are in the mix, the higher the permeability value is [32, 33].

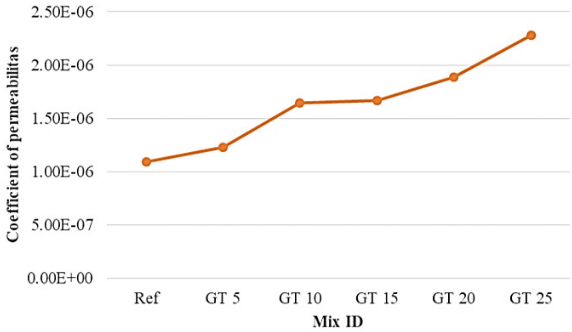


Fig. 6. Permeability coefficient results after testing using an air permeability apparatus.

G. Fourier Transform Infrared Spectroscopy

Figure 7 shows a peak at 3406.60 cm^{-1}, which indicates a water-related-OH group. The peak's intensity is lower in GT25 concrete, probably because its content has less water but increased strength and density [34].

The peak at 1649.50 cm^{-1} indicates the effect of additives on cement hydration and C-S-H formation. The peak at 1397.15 cm^{-1} related to carbonate ($CaCO_3$) is more clear in GT concrete, probably due to the additives that accelerate the carbonation. The peak at 865.77 cm^{-1} indicates a more vigorous C-S-H formation in GT10 and GT25, which contributes to the concrete's strength [35].

The 418.74 cm^{-1}, 599.71 cm^{-1}, and 708.59 cm^{-1} peaks, indicate an increase in silicate and aluminate phases in GT25 concrete that make it stronger and more resilient [36].

This FTIR analysis shows that the additives in GT concrete improve the concrete's mechanical properties and durability when compared to the Ref concrete.

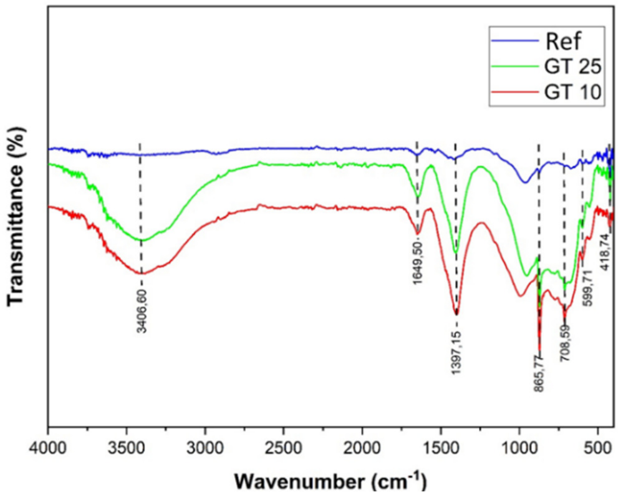


Fig. 7. FTIR of GT10, GT25, and standard concrete as reference (Ref).

H. X-ray Diffraction

Figure 8 presents the XRD analysis of Ref, GT10, and GT25 concrete. It is clear that Albite minerals have the highest peaks at 22.05°, 23.11°, and 28.15° [37]. The peak at 28.15° shows a decrease in intensity for GT10 and GT25, possibly due to the dilution effect and the chemical interaction with the concrete matrix. Kaolinite minerals were detected at the 35.57°, 39.56°, 53.28°, and 60.08° peaks in small amounts, while Quartz increased at the 26.51° peak in GT10 and GT25. Portlandite minerals demonstrated a decrease in intensity at the 17.96° peak due to a reaction with silica tailings to form a C-S-H phase [38]. Hydroxyapatite minerals are stable at the 10.44° and 11.62° peaks, while Calcite disappear at the 57.61° peak, possibly due to transformation or dissolution [39]. Magnetite mineral remains are detectable in all samples.

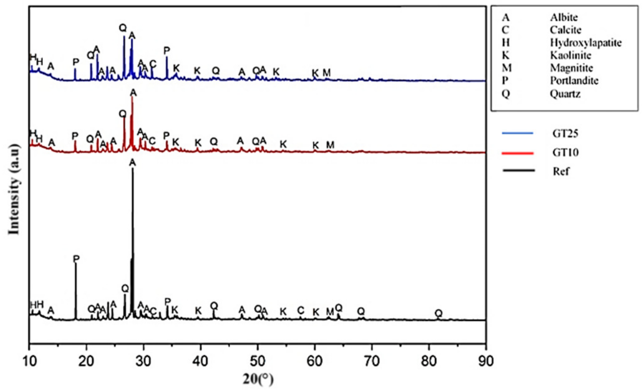


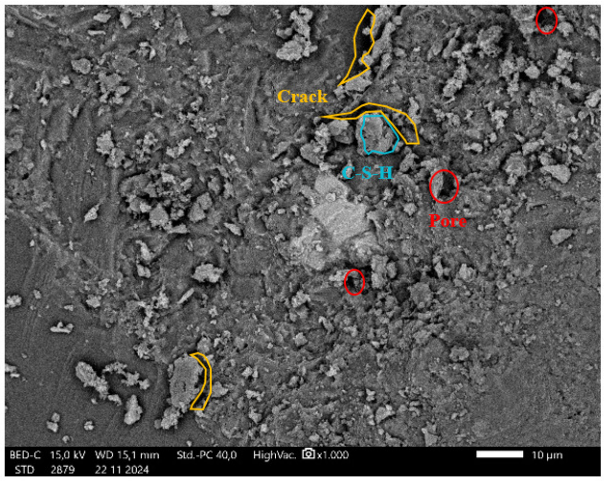
Fig. 8. XRD Pattern.

I. *Scanning Electron Microscopy*

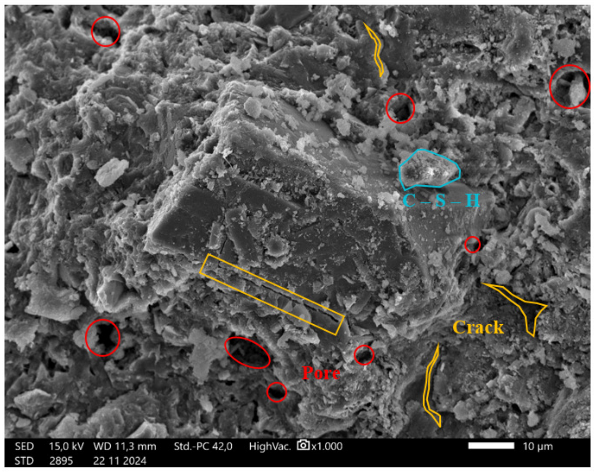
The SEM testing was conducted at the BRIN (National Research and Innovation Agency) laboratory with a Jeol JSM-IT200 machine to determine the microstructure and surface morphology of the concrete. It was performed on Ref concrete, GT10, and GT25. All concrete samples were aged for 28 days. Additionally, the SEM testing was performed on samples with GT powder. The 28-day-old concrete samples were crushed using a compressive strength machine, and SEM was then utilized to test the broken samples, which had a maximum thickness of 2.5 cm.

The SEM results revealed significant morphological differences in GT10 concrete compared to the Ref concrete. They were all characterized by a coarser structure and higher porosity, as shown in Figure 9(b). The GT25 concrete in particular, exhibited a more porous morphology with particle aggregation and uneven distribution, as displayed in Figure 9(c).

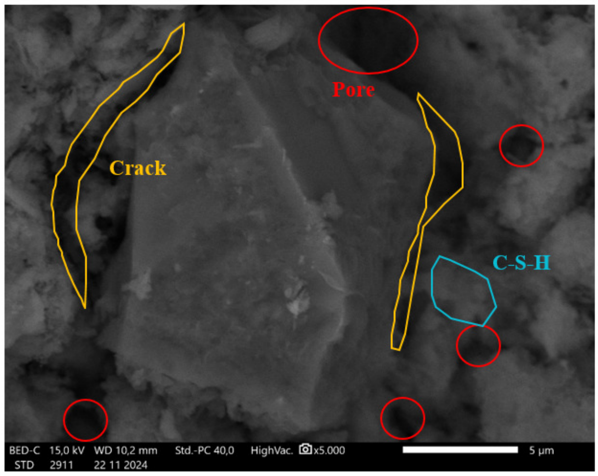
Figure 10 presents the results of the Elemental Distribution Analysis (EDS), which showed an increase in O content to 52.07%, with a decrease in Na, Si, and Al. There was also an increase in Ca to 30.20% indicating that there was a reaction between the tailings and the cement paste in order to produce calcium carbonate compounds [40]. The decrease in Si and Al indicates a reduction in the C-S-H phase that affects the compressive strength of concrete, whereas the rise in calcium makes concrete more resilient to chemical damage [41, 42].



(a)

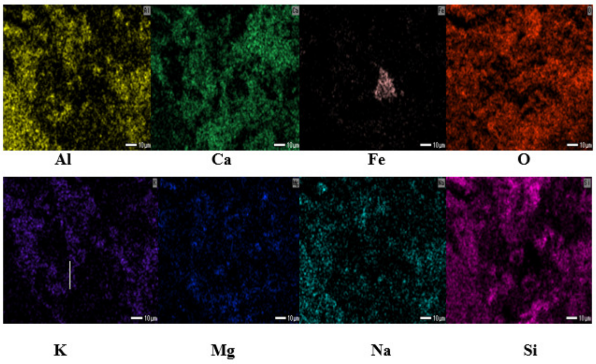


(b)

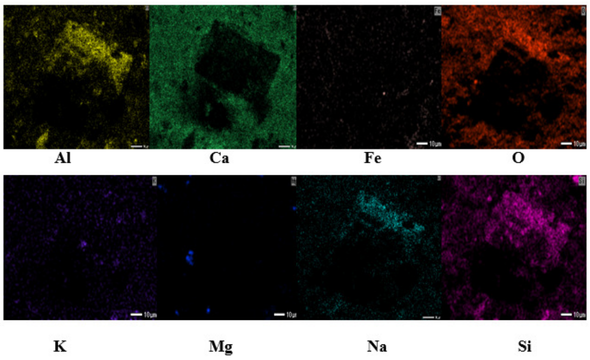


(c)

Fig. 9. Morphology and mineral crystal analysis of SEM results: (a) Reference, (b) GT10, (c) GT25.



(a)



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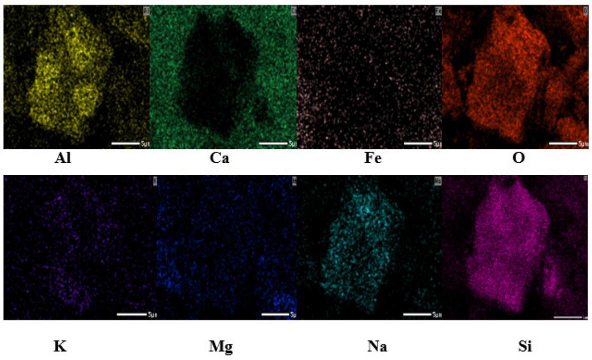

(c)

Fig. 10. Elemental distribution from SEM-Mapping on samples of: (a) Reference, (b) GT10, and (c) GT25.

The EDS results in GT25 concrete exhibited a decrease in the Ca content. This outcome suggests that excess tailings inhibited the calcium reactivity and the efficiency of C-S-H formation was reduced. The increase in Si and Al, indicates the formation of another silicate phase that can improve the chemical resistance but potentially reduce the mechanical strength of concrete.

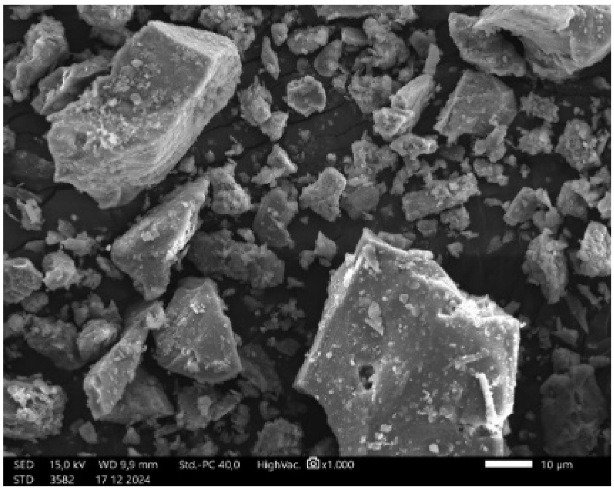

Fig. 11. Morphology and mineral crystal analysis of GT.

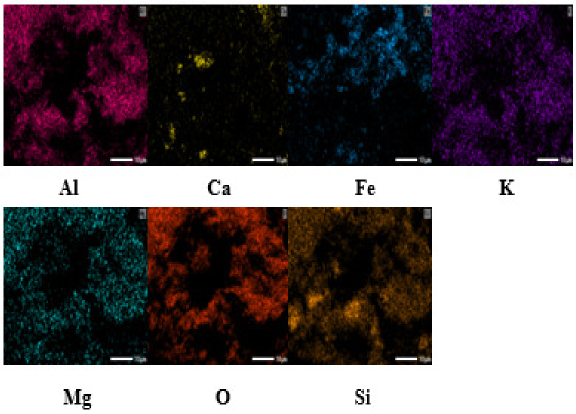

Fig. 12. EDS from SEM-Mapping on GT samples.

The addition of tailings as a partial replacement for aggregate or cement in concrete, can improve density and sustainability [43]. The SEM analysis of the tailings powder, as depicted in Figure 11, showed a layered structure with dense particle aggregates which filled the micropores of the concrete. The EDS analysis, as evidenced in Figure 12, revealed basic contents, such as O (45.06%), Si (22.16%), and Al (12.61%), which could potentially form C-S-H compounds, thus strengthening the concrete's compressive strength. The optimum tailings addition percentage to increase the density and durability of concrete, without significantly reducing the mechanical strength, is below 10%.

J. Toxicity Characteristic Leaching Procedure

At 28 days of age, GT25 concrete and GT went through a TCLP testing. The GT demonstrated high Pb levels (7.9 mg/L), which were above the permissible limit of 3 mg/L.

In GT25, the Pb concentration was under 0.01 mg/L, remaining far below the permissible limit. These results demonstrate that GT waste may be used successfully for sustainable concrete production.

TABLE III. TCLP TEST RESULTS FOR GT25 CONCRETE AND GT

Parameter	Unit	GT	GT25 concrete	Permissible limit
Lead	mg/L	7.9	< 0.01	3

IV. CONCLUSIONS

This research evaluated the use of Gold Tailings (GT) waste as a partial substitution of cement in concrete mixtures with various proportions (5%, 10%, 15%, 20%, and 25%). A series of thorough tests were carried out, including the chemical characterization of the material, Toxicity Characteristic Leaching Procedure (TCLP) testing, evaluation of concrete's physical and mechanical properties, and microstructure analysis through Fourier Transform Infrared (FTIR) Spectroscopy, X-ray Diffraction (XRD), and Electron Microscopy-Elemental Distribution Analysis (SEM-EDS).

The results showed that GT contain a chemical composition similar to that of pozzolanic materials (Fe_2O_3 at 8.52%, Al_2O_3 at 15.50%, SiO_2 at 49.01%). This indicates that there is a potential for GT to become a partial replacement for cement. A key finding of this study was the determination of the optimum percentage of GT usage (10-20%) that could maintain a compressive strength above 30 MPa, despite the reduction in workability. FTIR and XRD analyses detected the formation of C-S-H phases which led to increased strength. The SEM-EDS analysis in GT25 concrete showed a change in shape along with a decrease in calcium content.

One of the advantages of this research is that it proves that concrete using GT has very low Pb levels (<0.01 mg/L), making it environmentally safe. Finally, the novelty of this research lies in the fact that by applying GT as a concrete additive, it has been proven that up to a 10% substitution, the result is not only feasible and safe, but also supports sustainable development and promotes the concept of green concrete.

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REFERENCES

[1] H. Ziari, M. Zalnezhad, M. Ali Ziari, and E. Nasiri Amiri, "Substitution of the natural aggregate filler by coal waste powder (CWP) in microsurfacing surface treatment: Mix design and performance evaluation," *Construction and Building Materials*, vol. 354, Art. no. 129132, Nov. 2022, https://doi.org/10.1016/j.conbuildmat.2022.129132.

[2] M. Karimaei, F. Dabbaghi, A. Sadeghi-Nik, and M. Dehestani, "Mechanical performance of green concrete produced with untreated coal waste aggregates," *Construction and Building Materials*, vol. 233, Art. no. 117264, Feb. 2020, https://doi.org/10.1016/j.conbuildmat.2019.117264.

[3] M. Mohanty, D. R. Biswal, and S. S. Mohapatra, "A systematic review exploring the utilization of coal mining and processing wastes as secondary aggregate in sub-base and base layers of pavement," *Construction and Building Materials*, vol. 368, no. 0, Mar. 2023, https://doi.org/10.1016/j.conbuildmat.2023.130408.

[4] P. H.-M. Kinnunen and A. H. Kaksonen, "Towards circular economy in mining: Opportunities and bottlenecks for tailings valorization," *Journal of Cleaner Production*, vol. 228, pp. 153–160, Aug. 2019, https://doi.org/10.1016/j.jclepro.2019.04.171.

[5] I. Septiningsih and I. D. Kurniawan, "Pertambangan Emas dan Limbah yang Dihasilkannya : (Studi PT. Aneka Tambang)," *Arus Jurnal Sosial dan Humaniora*, vol. 4, no. 2, pp. 517–526, Aug. 2024, https://doi.org/10.57250/ajsh.v4i2.389.

[6] A. Upadhyay, T. Laing, V. Kumar, and M. Dora, "Exploring barriers and drivers to the implementation of circular economy practices in the mining industry," *Resources Policy*, vol. 72, no. C, Aug. 2021, https://doi: 10.1016/J.RESOURPOL.2021.102037.

[7] M. Gou, L. Zhou, and N. W. Y. Then, "Utilization of tailings in cement and concrete: A review," *Science and Engineering of Composite Materials*, vol. 26, no. 1, pp. 449–464, Jan. 2019, https://doi.org/10.1515/secm-2019-0029.

[8] I. A. Straupnik, "An overview of the environmental impact of coal industry waste," *IOP Conference Series: Earth and Environmental Science*, vol. 1070, no. 1, Art. no. 012004, Apr. 2022, https://doi.org/10.1088/1755-1315/1070/1/012004.

[9] D. Ürge-Vorsatz and A. Novikova, "Potentials and costs of carbon dioxide mitigation in the world's buildings," *Energy Policy*, vol. 36, no. 2, pp. 642–661, Feb. 2008, https://doi.org/10.1016/j.enpol.2007.10.009.

[10] G. Kurniawati, L. O. Nelfia, A. O. Irlan, and I. Sumeru, "Penyuluhan dan percontohan penggunaan limbah plastik untuk material bahan bangunan di lingkungan RPTRA, Jakarta Barat," *Journal Abdi Masyarakat Indonesia*, vol. 1, no. 3, pp. 68–73, Nov. 2019, doi: 10.25105/jamin.v1i3.6047.

[11] M. Syarif, A. R. Nanda, Nurnawaty, H. A. Imran, N. Karim, and A. Yusri, "Compressive Strength Analysis of Renewable Mortar after Portland Cement Replacement with Waste Ash," *Engineering, Technology & Applied Science Research*, vol. 14, no. 4, pp. 15056–15061, Aug. 2024, https://doi.org/10.48084/etasr.7489.

[12] A. M. R. Nurzamilov and P. S. A. Sitogasa, "Analisis Dampak Industri Semen Menggunakan Metode Life Cycle Assessment (LCA) Pada PT. Semen Z," *Globe: Publikasi Ilmu Teknik, Teknologi Kebumian, Ilmu Perkapalan*, vol. 2, no. 1, pp. 62–77, Jan. 2024, https://doi.org/10.61132/globe.v2i1.127.

[13] R. M. Balanay, R. P. Varela, A. Balbin, and M. A. Lavapiez, "Socially inclusive valorization of gold mill tailings from the small-scale gold mining sector," *Global Journal of Environmental Science and Management*, vol. 10, no. 4, pp. 2067–2082, Oct. 2024, https://doi.org/10.22034/gjesm.2024.04.34.

[14] R. A. I. Sari, S. E. Wallah, and R. S. Windah, "Pengaruh jumlah semen dan FAS terhadap kuat tekan beton dengan agregat yang berasal dari sungai," *Journal Sipil Statik*, vol. 3, no. 1, pp. 68–76, 2015.

[15] A. Balbin *et al.*, "Characterization and evaluation of gold mill tailings as an additive in cement-stabilized products," *IOP Conference Series: Material Science and Engineering*, vol. 1318, no. 1, Art. no. 012006, Oct. 2024, doi: 10.1088/1757-899X/1318/1/012006.

[16] R. Kazmi and M. Chakraborty, "Use of Coal Mining Wastes in the Construction Industry to Promote a Circular Economy: A Systematic Literature Review," Preprints, Aug. 2024, https://doi.org/10.20944/preprints202408.1621.v1.

[17] R. Giménez-García, R. Vigil de la Villa Mencía, V. Rubio, and M. Frías, "The Transformation of Coal-Mining Waste Minerals in the

Pozzolanic Reactions of Cements," *Minerals*, vol. 6, no. 3, Art. no. 64, Sep. 2016, https://doi.org/10.3390/min6030064.

[18] S. Yagüe, I. Sánchez, R. Vigil de la Villa, R. García-Giménez, A. Zapardiel, and M. Frías, "Coal-Mining Tailings as a Pozzolanic Material in Cements Industry," *Minerals*, vol. 8, no. 2, Art. no. 46, Feb. 2018, https://doi.org/10.3390/min8020046.

[19] L. Oksri-Nelfia, R. Akbar, and S. Astutiningsih, "A Study of the properties and microstructure of high-magnesium nickel slag powder used as a cement supplement," *IOP Conference Series: Materials Science and Engineering*, vol. 829, no. 1, Art. no. 012007, Dec. 2020, https://doi.org/10.1088/1757-899X/829/1/012007.

[20] "Standard Test Method for Slump of Hydraulic-Cement Concrete," ASTM C143/C143M-20, Advancing Standards Transforming Markets, 2020.

[21] R. Argane, M. Benzaazoua, R. Hakkou, and A. Bouamrane, "A comparative study on the practical use of low sulfide base-metal tailings as aggregates for rendering and masonry mortars," *Journal of Cleaner Production*, vol. 112, pp. 914–925, Jan. 2016, https://doi.org/10.1016/j.jclepro.2015.06.004.

[22] M. Pourbaba, R. Chakraborty, M. Pourbaba, A. Belarbi, and J. H. Yeon, "A New Insight into the Design Compressive Strength of Ultra-High Performance Concrete," *Buildings*, vol. 13, no. 12, Art. no. 12, Dec. 2023, https://doi:10.3390/buildings13122909.

[23] Y. Zhao, X. Gu, J. Qiu, W. Zhang, and X. Li, "Study on the Utilization of Iron Tailings in Ultra-High-Performance Concrete: Fresh Properties and Compressive Behaviors," *Materials*, vol. 14, no. 17, Art. no. 4807, Jan. 2021, https://doi.org/10.3390/ma14174807.

[24] A. R. Ghanizadeh, F. Safi Jahanshahi, and S. S. Naseralavi, "Intelligent modelling of unconfined compressive strength of cement stabilised iron ore tailings: a case study of Golgohar mine," *European Journal of Environmental and Civil Engineering*, vol. 28, no. 8, pp. 1759–1787, Jun. 2024, https://doi.org/10.1080/19648189.2023.2276133.

[25] "Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens," ASTM C496-96, Advancing Standards Transforming Markets, 1996.

[26] W. Gallala *et al.*, "Mechanical and radiation shielding properties of mortars with additive fine aggregate mine waste," *Annals of Nuclear Energy*, vol. 101, pp. 600–606, Mar. 2017, https://doi.org/10.1016/j.anucene.2016.11.022.

[27] B. Y. Nabiilah, L. O. Nelfia, and S. Astutiningsih, "An innovation of high-performance concrete by replacing cement with nickel slag powder," *International Journal on Livable Space*, vol. 4, no. 2, pp. 77–83, Sep. 2019, doi: 10.25105/livas.v4i2.5602.

[28] "Standard Test Method for Density, Absorption, and Voids in Hardened Concrete," ASTM C642-21, Advancing Standards Transforming Markets, 2021.

[29] S. W. M. Supit, R. Rumbayan, and S. Misilu, "Pengaruh pemanfaatan tailing terhadap kuat tekan, porositas dan absorpsi mortar Portland Composite Cement," *Jurnal Teknik Sipil Terapan*, vol. 1, no. 1, pp. 29–37, Aug. 2019, https://doi.org/10.47600/jtst.v1i1.222.

[30] L. O. Nelfia *et al.*, "Comprehensive characteristics of high-performance concrete with nickel slag as fine and coarse aggregate," *International Journal of Technology*, vol. 15, no. 6, pp. 1613–1631, Dec. 2024, doi: 10.14716/ijtech.v15i6.7184.

[31] "Standard Test Method for Measurement of the Permeability of Unsaturated Porous Materials by Flowing Air," ASTM D6539-13, Advancing Standards Transforming Markets, 2013.

[32] O. Onuaguluchi and Ö. Eren, "Cement mixtures containing copper tailings as an additive: durability properties," *Materials Research*, vol. 15, no. 6, pp. 1029–1036, Oct. 2012, doi: 10.1590/S1516-14392012005000129.

[33] W. Zhang, X. Gu, J. Qiu, J. Liu, Y. Zhao, and X. Li, "Effects of iron ore tailings on the compressive strength and permeability of ultra-high performance concrete," *Construction and Building Materials*, vol. 260, Art. no. 119917, Nov. 2020, https://doi.org/10.1016/j.conbuildmat.2020.119917.

[34] W. Quan *et al.*, "A new approach for improving the properties of tailings sand autoclaved aerated concrete - From a mineralogical perspective," *Construction and Building Materials*, vol. 441, Art. no. 137584, Aug. 2024, https://doi.org/10.1016/j.conbuildmat.2024.137584.

[35] B. Lothenbach, D. Jansen, Y. Yan, and J. Schreiner, "Solubility and characterization of synthesized 11 Å Al-tobermorite," *Cement and Concrete Research*, vol. 159, Art. no. 106871, Sep. 2022, https://doi.org/10.1016/j.cemconres.2022.106871.

[36] M. Y. A. Mollah, W. Yu, R. Schennach, and D. L. Cocke, "A Fourier transform infrared spectroscopic investigation of the early hydration of Portland cement and the influence of sodium lignosulfonate," *Cement and Concrete Research*, vol. 30, no. 2, pp. 267–273, Feb. 2000, https://doi.org/10.1016/S0008-8846(99)00243-4.

[37] S. Kishnan, A. T. Marsh, and S. A. Bernal, "Mechano-chemically and thermally activated montmorillonite clays as precursors for alkali-activated cements production," *41st Cement and Concrete Science Conference*, pp. 1–3, Leeds, UK., Sep 2022, https://eprints.whiterose.ac.uk/id/eprint/191690.

[38] X. M. Aretxabaleta, J. López-Zorrilla, C. Labbez, I. Etxebarria, and H. Manzano, "A potential C-S-H nucleation mechanism: atomistic simulations of the portlandite to C-S-H transformation," *Cement and Concrete Research*, vol. 162, Art. no. 106965, Dec. 2022, doi: 10.1016/j.cemconres.2022.106965.

[39] C. L. Freeman and J. H. Harding, "The transformation of amorphous calcium carbonate to calcite and classical nucleation theory," *Journal of Crystal Growth*, vol. 603, Art. no. 126978, Feb. 2023, https://doi.org/10.1016/j.jcrysgro.2022.126978.

[40] A. Saedi, A. Jamshidi-Zanjani, and A. K. Darban, "A review of additives used in the cemented paste tailings: Environmental aspects and application," *Journal of Environmental Management*, vol. 289, Art. no. 112501, Jul. 2021, https://doi.org/10.1016/j.jenvman.2021.112501.

[41] S. Goyal, M. Kumar, D. S. Sidhu, and B. Bhattacharjee, "Resistance of mineral admixture concrete to acid attack," *Journal of Advanced Concrete Technology,* vol. 7, no. 2, pp. 273–283, Jun. 2009, doi: 10.3151/jact.7.273.

[42] Y. Wang, H. Liao, Y. Wu, and J. Yang, "Effect of Si content on microstructure and mechanical properties of Al–Si–Mg alloys," *Materials & Design*, vol. 53, pp. 634–638, Jan. 2014, https://doi.org/10.1016/j.matdes.2013.07.067.

[43] D. Adiguzel, S. Tuylu, and H. Eker, "Utilization of tailings in concrete products: A review," *Construction and Building Materials*, vol. 360, Art. no. 129574, Dec. 2022, https://doi.org/10.1016/j.conbuildmat.2022.129574.