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DEVELOPMENT OF TAILINGS-BASED FORMULATIONS AS AN ENVIRONMENTALLY FRIENDLY BUILDING MATERIAL: A LABORATORY-SCALE STUDY IN MIMIKA REGENCY, CENTRAL PAPUA, INDONESIA

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Abstract
Tailings management remains a persistent environmental challenge in mining regions, including Mimika Regency, Central Papua, Indonesia, where impoundment remains the dominant disposal practice. Building on prior geochemical and mineralogical characterization of local tailings, this study developed and evaluated three tailings-cement formulations, F1 (60:40), F2 (70:30), and F3 (80:20) tailings-to-cement ratio by mass, as candidate non-structural building materials. Specimens were cast as 50 mm cubes and tested for compressive strength at 7, 14, and 28 days, and for water absorption and density at 28 days, following procedures consistent with Indonesian National Standard SNI 03-0349-1989. Twenty-eight-day compressive strength reached 17.90 ± 0.57 MPa (F1), 12.21 ± 0.60 MPa (F2), and 7.23 ± 0.35 MPa (F3), with water absorption of 9.14-15.25% and density of 1.83-1.99 g/cm3. Formulations F1 and F2 satisfied Grade I, and F3 satisfied Grade II, of the applicable national standard for solid concrete brick used in wall construction, indicating that all three formulations, including the highest tailings substitution level tested (80%), are technically viable as non-structural building materials.

Keywords: building material; circular economy; compressive strength; Mimika; mine tailings

INTRODUCTION

Mining activities generate substantial quantities of tailings as solid waste, and their management remains a persistent global challenge. Tailings storage facilities remain the dominant disposal approach in most jurisdictions, an approach repeatedly associated with long-term environmental risk; remote sensing-based monitoring of process water ponds has been proposed specifically to help prevent tailings dam failures (Cacciuttolo & Cano, 2023). A review of copper mine tailings governance in Chile over more than a century highlighted how inadequate long-term management of tailings storage facilities continues to pose socio-environmental risks even in mature regulatory contexts (Cacciuttolo & Atencio, 2022). More broadly, the chemical composition of mine tailings has been linked to socio-environmental risks in both copper and gold mining contexts in Chile and Peru, underscoring the need for responsible and safe tailings management practices (Cacciuttolo et al., 2023). Related environmental concerns include mineral weathering and metal leaching under meteoric conditions (Kaba et al., 2023) and the toxicological impact of acid mine drainage on aquatic organisms such as zebrafish and water fleas (Yoon & Yoon, 2022).

At the same time, tailings often retain considerable proportions of reactive silica and alumina, positioning them as potentially viable raw materials for construction applications rather than solely as waste requiring long-term disposal. Systematic reviews of tailings-based geopolymer production confirm a rapidly expanding evidence base for this valorization pathway (Qaidi et al., 2022), and detailed characterization studies of iron ore tailings have clarified both the environmental risks and the material properties relevant to reuse (Wang et al., 2023). This potential has driven growing research interest in tailings valorization within a circular economy framework, spanning applications from cementitious composites and geopolymers to non-structural building blocks and masonry units (Cobîrzan et al., 2022; Hameed et al., 2024).

In the Indonesian context, mining-affected regions face similar challenges. Studies of bauxite tailings and red mud in West Kalimantan have highlighted both the resource potential and the environmental complexity of mining residues in Indonesia (Al Hakim et al., 2023), while mineralogical studies of iron mining areas in South Sulawesi have documented acid mine drainage generation risks associated with sulfide-bearing tailings (Saputra et al., 2023). In Mimika Regency, Central Papua, Indonesia, mining operations generate substantial volumes of tailings that are predominantly managed through impoundment. Building on this concern, the authors' prior study characterized the geochemical and mineralogical properties of tailings along the Kali Kabur River in this region using X-ray fluorescence, X-ray diffraction, and scanning electron microscopy, revealing that the material is dominated by silicate and oxide minerals with relatively stable physical and mineralogical characteristics, and identifying reutilization potential as a secondary resource (Putri & Rahim, 2025).

That earlier study, however, was limited to the characterization stage, a pattern that recurs broadly in the wider literature. Studies of auriferous tailings deposits, for example, have identified strong reuse potential based on geochemical and mineralogical evidence without proceeding to formulation and performance validation (Lemos et al., 2023), while heterogeneity assessments of legacy tailings deposits have similarly focused on characterization to inform remediation and reprocessing decisions rather than direct material development (Surrette et al., 2024). A more incremental approach, developing simple cement-bound, non-structural formulations validated through standard physical and mechanical testing, offers a realistic pathway for translating site-specific characterization data into an applied, laboratory-validated material, consistent with the objectives of an early-stage research scheme.

This study addresses this gap by directly linking the geochemical and mineralogical characterization previously established for Mimika tailings (Putri & Rahim, 2025) to the design, formulation, and laboratory-scale performance evaluation of a tailings-based, cement-bound building material. Three tailings-to-cement formulations, namely 60:40, 70:30, and 80:20 (hereafter F1, F2, and F3), were developed and evaluated in terms of compressive strength, water absorption, and density at multiple curing ages. Accordingly, the specific objectives of this study are to: (i) develop and prepare tailings-cement formulations at three substitution ratios; (ii) evaluate their basic physical and mechanical properties; and (iii) determine the optimum formulation for further development as an environmentally friendly, non-structural building material.

METHOD

Materials and Sample Preparation

Tailings were collected from the same location used in the authors' prior geochemical and mineralogical characterization study in Mimika Regency (Putri & Rahim, 2025), using purposive sampling across multiple points to obtain a representative composite sample. Ordinary Portland Cement (OPC) and clean water were used as the binder and mixing water, respectively. Tailings were oven-dried at approximately 105°C to constant weight, sieved to remove particles retained above 4.75 mm, and homogenized prior to batching, following preparation principles consistent with prior mineralogical characterization of tailings and mining residues (Silva et al., 2022).

Mix Design and Specimen Preparation

Three tailings-to-cement formulations were prepared by mass: F1 (60:40), F2 (70:30), and F3 (80:20), consistent with substitution-based mix design approaches reported for iron ore tailings as fine aggregate replacement in concrete (Hameed et al., 2024) and for tailings-based masonry unit production (Cobîrzan et al., 2022). The water-to-cement ratio was determined through small-scale trial mixing to achieve consistent workability across formulations and was subsequently held constant during specimen casting. Specimens were cast as 50 x 50 x 50 mm cubes in three layers, each compacted with approximately 25 tamps, following a procedure consistent with standard mortar cube preparation (SNI 03-6825-2002 / ASTM C109 principles) and compressed block preparation approaches used for tailings-based unfired units (Thejas & Hossiney, 2022).

Curing and Testing Procedures

Specimens were demoulded after 24 hours and subsequently water-cured under ambient conditions until the designated testing age. Triplicate specimens (n = 3) were prepared for each formulation-age combination for compressive strength testing (7, 14, and 28 days), and a separate set of triplicate specimens per formulation was prepared for water absorption and density testing at 28 days. Compressive strength was determined by loading specimens to failure using a Compression Testing Machine (CTM) and dividing the maximum load by the measured cross-sectional area, consistent with SNI 03-0349-1989 and with mechanical testing approaches applied to other tailings-based cementitious materials (Zhang et al., 2022; Akande et al., 2023). Water absorption was determined from oven-dry mass (105-110°C, 24 hours) and saturated mass after 24-hour immersion, and density was calculated from dry mass and geometrically determined specimen volume.

Data Analysis

Results were analyzed descriptively (mean ± standard deviation, n = 3 per condition) and compared across formulations and curing ages. Compressive strength and water absorption results were additionally benchmarked against the quality grading criteria of SNI 03-0349-1989 for solid concrete brick used in wall construction.

RESULTS AND DISCUSSION

Compressive Strength Development

Table 1 summarizes the mean compressive strength of the three formulations at 7, 14, and 28 days (n = 3 per condition).

Table 1. Mean compressive strength (± SD, n = 3) by formulation and curing age

Formulation	7 days (MPa)	14 days (MPa)	28 days (MPa)	28 days (kg/cm2)
F1 (60:40)	11.06 ± 0.34	13.75 ± 0.43	17.90 ± 0.57	182.6
F2 (70:30)	7.71 ± 0.33	10.49 ± 0.42	12.21 ± 0.60	124.5
F3 (80:20)	4.39 ± 0.22	6.17 ± 0.31	7.23 ± 0.35	73.8

Compressive strength increased consistently with curing age across all formulations, and decreased with increasing tailings content at every age, reflecting the role of cement as the primary binding agent. This pattern is consistent with mechanical performance trends reported for other tailings-based cementitious materials, where iron tailings used as fine aggregate replacement improved compressive strength at moderate replacement levels while higher replacement reduced pozzolanic contribution (Akande et al., 2023; Zhang et al., 2022). Similar threshold-dependent behavior has been reported for gold ore tailings in geopolymer concrete, where mechanical properties were highly sensitive to tailings proportion and curing regime (Lokesha et al., 2023, 2025), and for copper slag additions to mortar, where compressive strength could be reliably predicted from mix proportions using regression-based modeling (Yan et al., 2022). A broader review of ultra-high-performance concrete incorporating metal mine tailings similarly confirms that tailings fineness and content strongly govern mechanical outcomes across tailings types (Li et al., 2024).

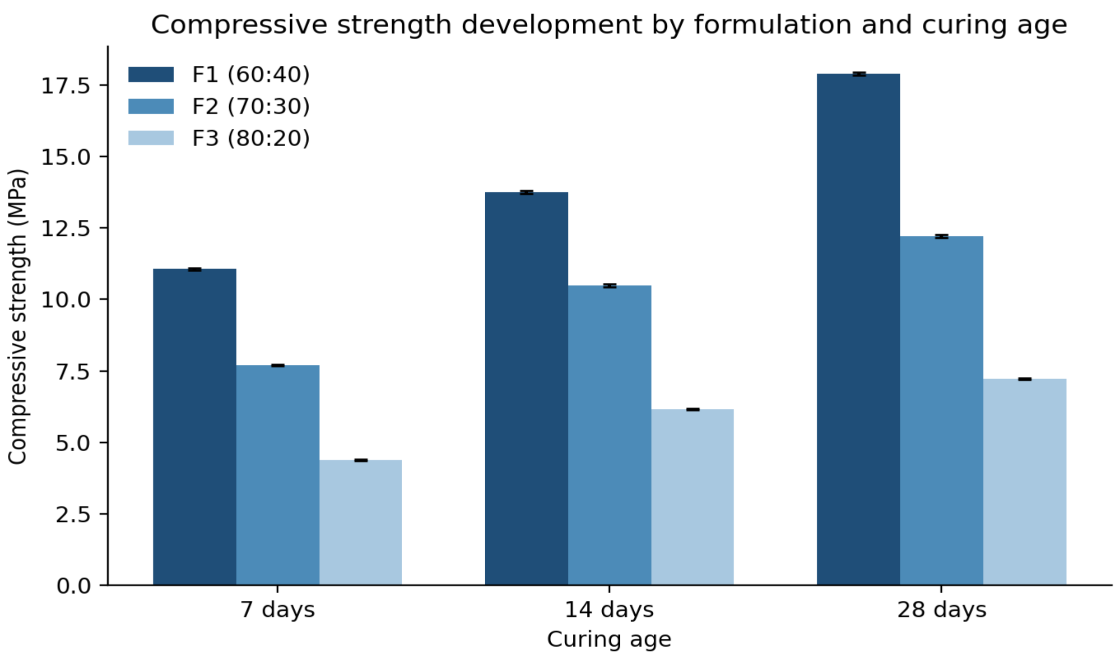

Figure 1. Compressive strength development by formulation and curing age (error bars: ±1 SD, n = 3).

Water Absorption and Density

Table 2. Water absorption and density (± SD, n = 3) at 28-day curing age

Formulation	Water absorption (%)	Density (g/cm3)	Density (kg/m3)
F1 (60:40)	9.14 ± 0.06	1.988 ± 0.022	1988
F2 (70:30)	11.79 ± 0.04	1.916 ± 0.021	1916
F3 (80:20)	15.25 ± 0.14	1.830 ± 0.016	1830

Water absorption increased progressively with tailings content, while density decreased correspondingly, consistent with a reduction in cement paste content available to fill pore spaces and bind particles into a denser matrix. Comparable porosity-related trends have been reported for masonry units incorporating mining waste (Cobîrzan et al., 2022) and for compressed unfired blocks made with iron ore tailings and slag, where binder content was similarly found to govern water absorption behavior (Thejas & Hossiney, 2022). Mineralogical characterization of magnetic tailings from phosphate-ore processing has likewise shown that particle morphology and fineness materially affect matrix density in tailings-based composites (Silva et al., 2022).

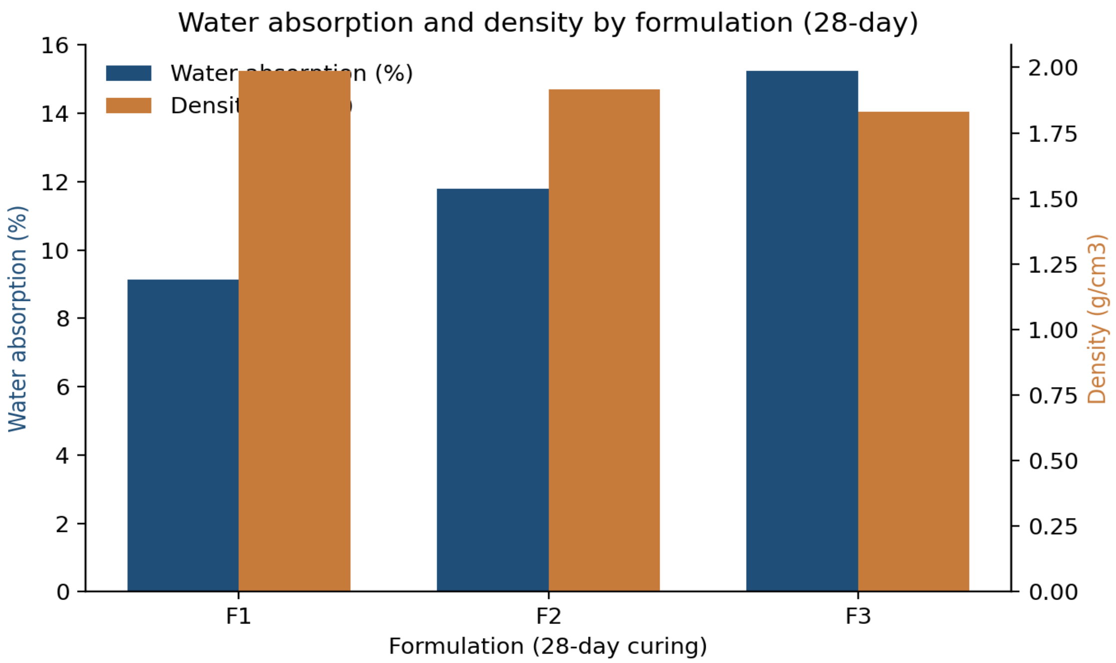

Figure 2. Water absorption and density by formulation at 28-day curing age.

Benchmarking against National Standards and Formulation Selection

Benchmarked against SNI 03-0349-1989, which classifies solid concrete brick for wall construction into four grades (Grade I: ≥100 kg/cm2, Grade II: ≥70 kg/cm2, Grade III: ≥40 kg/cm2, Grade IV: ≥25 kg/cm2, with maximum water absorption of 25% and 35% for Grades I and II respectively), the 28-day results show that F1 (182.6 kg/cm2) and F2 (124.5 kg/cm2) both exceed the Grade I threshold, while F3 (73.8 kg/cm2) satisfies Grade II. All three formulations also met the corresponding water absorption limits. This indicates that even at the highest tested tailings substitution level (80%), the resulting material remains suitable as non-structural solid concrete brick, comparable to feasibility findings reported for iron ore tailings as fine aggregate with fiber reinforcement (Hameed et al., 2024) and for high-strength concrete produced entirely from waste rock aggregates (Li et al., 2025).

Beyond mechanical and physical performance, the tailings valorization literature highlights an additional environmental co-benefit relevant to this study: the potential immobilization of heavy metals within cementitious or geopolymeric matrices. Gold mine tailings processed into one-part geopolymers through alkaline hydrothermal activation have demonstrated effective structural incorporation of tailings constituents (Liu et al., 2021), while ecological risk assessments of tailings-affected soils have underscored the importance of stabilizing tailings-derived metals to reduce environmental exposure (Adebayo et al., 2022). This co-benefit is particularly relevant to the broader research context in Mimika Regency, where flotation tailings recovery studies from comparable copper-gold operations elsewhere have highlighted the value of treating tailings as a secondary raw material rather than waste alone (Trifunovic et al., 2024). Framing tailings-based building material development as simultaneously a waste-valorization and a pollution-mitigation strategy therefore strengthens its relevance to the regional environmental agenda, and aligns with broader circular economy pathways proposed for red mud and other mineral residues in construction and soil improvement applications (Raj et al., 2024).

From a formulation-selection standpoint, F1 offers the highest mechanical performance and lowest water absorption, favoring applications where higher reliability is prioritized, while F3 offers the greatest tailings utilization rate per unit of material while still meeting Grade II requirements. Overall, these results directly address the three research questions posed in this study: three distinct tailings-cement formulations were successfully developed and evaluated; all three exhibited measurable, age-dependent physical and mechanical properties within recognized national standard ranges; and F1 emerges as the optimal formulation when mechanical performance is prioritized, while F3 represents the optimal formulation when tailings utilization is prioritized, subject to meeting the applicable minimum quality grade.

CONCLUSION

This study developed and laboratory-evaluated three tailings-cement formulations (F1 60:40, F2 70:30, F3 80:20) as candidate environmentally friendly, non-structural building materials using tailings from Mimika Regency, Central Papua, Indonesia. Twenty-eight-day compressive strengths of 17.90, 12.21, and 7.23 MPa were obtained for F1, F2, and F3 respectively, with water absorption between 9.14% and 15.25% and density between 1.83 and 1.99 g/cm3. All three formulations satisfied at least Grade II of SNI 03-0349-1989 for solid concrete brick used in wall construction, with F1 and F2 satisfying Grade I. These results confirm that tailings from Mimika can be viably valorized into a non-structural building material even at a high substitution level (80%), directly linking prior geochemical characterization work (Putri & Rahim, 2025) to an applied, laboratory-validated outcome. Future work should extend this evaluation to durability under environmental exposure and leachate testing, informed by tailings storage risk-monitoring approaches such as those proposed by Cacciuttolo and Cano (2023) and heterogeneity-informed remediation strategies such as those described by Surrette et al. (2024), to further substantiate the environmental safety claims associated with heavy metal immobilization ahead of pilot-scale application.

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CONFLICT OF INTEREST

The author declares no conflict of interest.

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