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Experimental Investigation of Geotechnical and Mechanical Properties of Iron Ore Mine Tailings for Sustainable Use in Concrete and Civil Engineering Applications

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Abstract
The increasing accumulation of iron ore mine tailings and the depletion of natural construction materials have necessitated the exploration of sustainable alternatives for civil engineering applications. This study presents an experimental investigation on the geotechnical and mechanical properties of iron ore mine tailings to evaluate their suitability for use in concrete and construction-related works. Iron ore mine tailings were characterized for their physical, chemical, and mineralogical properties and were used as partial replacements for natural fine aggregates in concrete at varying proportions. Geotechnical behavior was assessed through compaction and shear strength tests, while mechanical performance was evaluated using compressive, split tensile, and flexural strength tests. Durability characteristics were examined through water absorption and sorptivity measurements. The results indicate that concrete incorporating iron ore mine tailings at replacement levels up to 20% exhibits comparable or improved mechanical performance relative to conventional concrete, attributed to enhanced particle packing and matrix densification. Geotechnical test results further demonstrate favorable compaction characteristics and improved shear resistance, particularly when tailings are stabilized. However, higher replacement levels resulted in reduced workability and increased permeability. Overall, the findings confirm that iron ore mine tailings can be effectively utilized as a sustainable alternative material in concrete and geotechnical applications, contributing to waste reduction and resource conservation in the construction industry.

1. INTRODUCTION:

1.1 Background and Motivation

The rapid expansion of the mining industry has resulted in the generation of large volumes of iron ore mine tailings, which are commonly stored in tailings ponds or disposed of in open land areas. These tailings, often considered as industrial waste, occupy vast land resources and pose long-term environmental challenges. At the same time, the construction industry continues to face increasing demand for natural aggregates, leading to excessive exploitation of river sand and other natural resources. This dual challenge of waste accumulation and resource depletion has motivated researchers to explore alternative materials that can be sustainably integrated into civil engineering applications. Iron ore mine tailings, owing to their fine particle size and mineral composition, have emerged as a potential substitute material in concrete and geotechnical works, thereby offering a promising pathway for sustainable construction practices.

1.2 Environmental Concerns Associated with Mine Tailings

The uncontrolled disposal of mine tailings presents serious environmental risks, including land degradation, dust pollution, and contamination of surface and groundwater resources. Tailings storage facilities require continuous monitoring and maintenance to prevent structural failure and leakage, which may result in severe ecological and socio-economic consequences. Additionally, the fine nature of iron ore tailings facilitates wind erosion, leading to air quality deterioration in surrounding areas. Addressing these environmental concerns necessitates the development of safe and effective reuse strategies that minimize the need for long-term storage while ensuring environmental protection. Utilizing mine tailings in construction materials offers a practical solution to reduce disposal volumes and mitigate associated environmental hazards.

1.3 Need for Sustainable Construction Materials

The construction sector is one of the largest consumers of natural resources, particularly aggregates and cement, whose production contributes significantly to environmental degradation and carbon emissions. Growing awareness of sustainability has prompted the search for eco-friendly materials that can reduce the environmental footprint of construction activities. Incorporating industrial by-products such as iron ore mine tailings into concrete and civil engineering applications aligns with the principles of sustainable development by conserving natural resources, lowering waste disposal requirements, and promoting circular material use. However, the successful adoption of such alternative materials requires a thorough understanding of their engineering behavior and performance characteristics.

1.4 Objectives and Scope of the Study

The primary objective of this study is to experimentally investigate the geotechnical and mechanical properties of iron ore mine tailings to evaluate their suitability for sustainable use in concrete and civil engineering applications. The study focuses on the characterization of physical, chemical, and engineering properties of mine tailings and examines their influence when used as a construction material. The scope of the work includes assessing geotechnical behavior relevant to civil works and evaluating mechanical performance in concrete mixtures, with an emphasis on identifying practical and environmentally responsible applications. The findings aim to contribute to the effective utilization of mine tailings as a viable alternative material in the construction industry.

2. PROPERTIES OF IRON ORE MINE TAILINGS

The suitability of iron ore mine tailings for use in civil engineering applications largely depends on their physical, chemical, and mineralogical characteristics. These properties govern the behavior of tailings when incorporated into concrete, stabilized soil systems, or other construction materials. A detailed understanding of these characteristics is therefore essential before proposing their use as alternative construction materials.

2.1 Physical Properties

Iron ore mine tailings are generally characterized by a fine particle size distribution, as they are produced during the beneficiation and grinding processes of iron ore extraction. The particle size distribution of tailings typically falls within the silt to fine sand range, with a significant proportion of particles finer than natural river sand. This finer grading influences packing density, water demand, and workability when tailings are used in concrete or cementitious systems.

The specific gravity of iron ore tailings is often comparable to or slightly higher than that of natural fine aggregates, owing to the presence of iron-bearing minerals. Bulk density values, however, tend to be lower due to the fine and angular nature of the particles, which results in increased void content. These physical characteristics can affect compaction behavior in geotechnical applications and influence fresh concrete properties such as flowability and segregation resistance. Consequently, appropriate grading control and mix optimization are required to achieve satisfactory performance.

2.2 Chemical and Mineralogical Characteristics

The chemical composition of iron ore mine tailings is primarily dominated by silica, iron oxides, alumina, and smaller quantities of calcium and magnesium oxides. The relative proportions of these oxides depend on the source of the ore and the beneficiation process employed. In many cases, the silica-rich nature of tailings makes them suitable for use as inert or partially reactive materials in cement-based systems.

Mineralogically, iron ore tailings commonly contain quartz as the major phase, along with hematite, magnetite, and minor amounts of other silicate and oxide minerals. These mineral phases influence the reactivity and bonding behavior of tailings in cementitious matrices. While quartz-rich tailings generally act as filler materials, studies have shown that mechanical or chemical activation can enhance their surface reactivity, contributing to improved interfacial bonding and strength development in concrete and blended cement systems.

2.3 Engineering Significance of Tailings Properties

The physical and chemical characteristics of iron ore mine tailings play a crucial role in determining their engineering performance. Fine particle size and angularity can improve particle packing and matrix densification at optimized replacement levels, leading to acceptable or enhanced mechanical strength. However, excessive fines may increase water demand and reduce workability if not properly managed.

From a geotechnical perspective, the density, grading, and mineral composition of tailings influence compaction characteristics, shear strength, and stability when used in embankments or stabilized soil layers. Chemically, the predominantly inert nature of tailings reduces the risk of adverse reactions, while their mineral composition allows compatibility with cementitious binders. Overall, the combined assessment of physical, chemical, and mineralogical properties confirms that iron ore mine tailings can be considered a viable alternative material for sustainable civil engineering applications, provided that their inherent characteristics are adequately addressed through appropriate design and processing methods.

3. REVIEW OF EARLIER RESEARCH

3.1 Utilization of Iron Ore Mine Tailings in Concrete

Early investigations into the use of iron ore mine tailings in concrete primarily focused on their feasibility as substitutes for natural fine aggregates. Research demonstrated that iron ore tailings could be successfully incorporated into both conventional and high-performance concrete mixtures when suitable mix design modifications were applied. In particular, studies on ultra-high performance concrete reported that tailings contributed to improved particle packing density due to their fine size, resulting in dense microstructures and acceptable strength performance. However, these studies also emphasized the need for controlled replacement levels to avoid excessive water demand and loss of workability [1].

Subsequent experimental works extended these findings to normal-strength concrete, where iron ore tailings were used as partial or full replacements for river sand. These studies consistently highlighted that tailings can serve as viable aggregate alternatives, reducing dependency on natural sand resources while maintaining structural integrity. The feasibility of tailings-based concrete was further validated through applications in precast elements such as interlocking concrete pavers, demonstrating compliance with standard strength and functional requirements [2], [4], [7].

3.2 Mechanical Performance of Tailings-Based Concrete

The mechanical behavior of concrete incorporating iron ore mine tailings has been extensively studied, with particular emphasis on compressive strength development. Experimental results revealed that moderate replacement of natural sand with tailings often resulted in comparable or slightly improved compressive strength due to enhanced particle packing and improved interfacial transition zones. However, excessive tailings content was shown to negatively affect strength, primarily due to increased porosity and reduced workability [1], [2], [7].

Research involving mechanochemical activation of iron ore tailings further demonstrated that treated tailings could enhance compressive strength by increasing surface reactivity and improving bonding with the cement matrix. These findings suggest that processing techniques can significantly influence the mechanical performance of tailings-based concrete. Microstructural investigations also supported these observations by linking strength development to hydration products and matrix densification [6], [9], [12].

3.3 Geotechnical Applications of Mine Tailings

Beyond concrete applications, iron ore mine tailings have been investigated for use in geotechnical and highway engineering works. Studies involving lime–cement stabilization of tailings-soil mixtures reported improved shear strength and enhanced load-bearing capacity, indicating their suitability for subgrade and embankment construction. These investigations highlighted that proper stabilization not only enhances mechanical performance but also mitigates environmental risks associated with raw tailings disposal [5], [14].

Additionally, tailings have been utilized in autoclaved aerated concrete and other lightweight construction materials, where their mineral composition contributes to phase formation and pore structure development. Such applications demonstrate the versatility of iron ore tailings in geotechnical and structural systems beyond conventional concrete [10], [11].

3.4 Environmental and Durability Aspects

Environmental sustainability has been a key motivation for the reuse of iron ore mine tailings in construction materials. Studies evaluating the environmental feasibility of tailings-based products reported reduced waste disposal requirements and conservation of natural aggregates. The use of tailings in concrete pavers and stabilized soil systems was shown to lower the environmental footprint while maintaining acceptable engineering performance [4], [5].

Durability-related investigations indicated that tailings-based concrete exhibits performance comparable to conventional concrete when designed appropriately. Microstructural studies on lime-pozzolana systems and nanosilica-modified binders provided insights into long-term hydration and durability behavior relevant to tailings utilization. Furthermore, research on ceramic and glass-ceramic products derived from iron ore tailings demonstrated stable physical properties, supporting their long-term applicability in construction environments [6], [8], [9].

4. EXPERIMENTAL PROGRAM AND METHODOLOGY

The experimental program was designed to evaluate the suitability of iron ore mine tailings for use in concrete and civil engineering applications by systematically assessing their geotechnical, mechanical, and durability performance. The methodology involved material characterization, mix proportioning, specimen preparation, and standardized laboratory testing.

4.1 Materials Used

Ordinary Portland Cement (OPC) conforming to relevant standards was used as the primary binder in all concrete mixtures. Natural river sand was employed as fine aggregate, while crushed stone aggregates were used as coarse aggregates. Iron ore mine tailings collected from a beneficiation plant were used as a partial replacement for natural fine aggregate. Prior to use, the tailings were oven-dried and sieved to remove oversized particles.

The physical properties of the materials used in the study are summarized in Table 1.

Table 1: Physical Properties of Materials Used

Material	Specific Gravity	Bulk Density (kg/m³)	Remarks
Cement	3.15	—	OPC
Natural fine aggregate	2.60–2.65	1450–1550	River sand
Coarse aggregate	2.70	1500–1600	Crushed stone
Iron ore mine tailings	2.8–3.2	1200–1400	Fine, angular

4.2 Mix Proportioning and Sample Preparation

Concrete mixes were prepared by partially replacing natural fine aggregate with iron ore mine tailings at different replacement levels to study their influence on performance. A control mix without tailings was used for comparison. The water–cement ratio was maintained constant for all mixes to ensure consistency in results.

Table 2: Concrete Mix Proportions with Iron Ore Mine Tailings

Mix ID	Tailings Replacement (%)	Cement (kg/m³)	Fine Aggregate (kg/m³)	Tailings (kg/m³)	Coarse Aggregate (kg/m³)	Water–Cement Ratio
CM	0	350	700	0	1200	0.45
TM10	10	350	630	70	1200	0.45
TM20	20	350	560	140	1200	0.45
TM30	30	350	490	210	1200	0.45
TM40	40	350	420	280	1200	0.45

Concrete was mixed in a laboratory mixer to achieve uniform consistency. Fresh concrete was cast into standard molds and compacted using vibration. Specimens were demolded after 24 hours and cured in water at room temperature until the specified testing ages.

4.3 Testing Procedures

To comprehensively assess the performance of iron ore mine tailings, geotechnical, mechanical, and durability-related tests were conducted following standard laboratory procedures.

4.3.1 Geotechnical Tests

Geotechnical tests were performed on iron ore mine tailings and tailings-based blends to evaluate their suitability for earthwork and stabilized soil applications. Compaction characteristics were determined using standard Proctor tests to obtain optimum moisture content and maximum dry density. Shear strength behavior was assessed through direct shear tests under controlled normal stresses.

Table 3: Geotechnical Tests Conducted

Test	Standard Followed	Purpose
Particle size distribution	IS / ASTM standard	Classification of tailings
Standard Proctor test	IS 2720 (Part 7)	OMC and MDD
Direct shear test	IS 2720 (Part 13)	Shear strength parameters
California Bearing Ratio (CBR)	IS 2720 (Part 16)	Subgrade suitability

4.3.2 Mechanical Strength Tests

Mechanical performance of tailings-based concrete was evaluated through compressive strength, split tensile strength, and flexural strength tests. Specimens were tested at curing ages of 7, 28, and 56 days to study strength development.

Table 4: Mechanical Strength Tests

Test	Specimen Type	Standard	Testing Age (Days)
Compressive strength	Cube (150 mm)	IS 516	7, 28, 56
Split tensile strength	Cylinder (150×300 mm)	IS 5816	28
Flexural strength	Prism (100×100×500 mm)	IS 516	28

4.3.3 Durability-Related Tests

Durability characteristics were assessed to examine the long-term performance of tailings-based concrete. Water absorption and sorptivity tests were conducted to evaluate permeability and resistance to moisture ingress.

Table 5: Durability-Related Tests

Test	Standard	Purpose
Water absorption	ASTM C642	Porosity assessment
Sorptivity	ASTM C1585	Capillary water uptake
Density measurement	IS 516	Quality assessment

5. RESULTS AND DISCUSSION

This section presents and discusses the experimental results obtained from geotechnical and concrete performance tests conducted on iron ore mine tailings and tailings-based concrete mixtures. The results are analyzed statistically and compared with conventional materials to evaluate feasibility and performance trends.

5.1 Geotechnical Behavior of Iron Ore Mine Tailings

The geotechnical properties of iron ore mine tailings were evaluated through compaction, shear strength, and bearing capacity tests. The results indicate that tailings exhibit favorable compaction characteristics due to their fine particle size and mineral density.

Table 6: Compaction Characteristics of Iron Ore Mine Tailings

Material	OMC (%)	MDD (kN/m³)
Natural soil (reference)	14.5	17.8
Iron ore mine tailings	12.2	18.6
Tailings + lime–cement	11.5	19.2

The lower optimum moisture content (OMC) and higher maximum dry density (MDD) of tailings compared to natural soil indicate improved compaction efficiency. Stabilized tailings exhibited an increase in dry density of approximately 7–8%, demonstrating their suitability for subgrade and embankment applications.

Table 7: Shear Strength Parameters of Tailings

Material	Cohesion, c (kPa)	Friction Angle, φ (°)
Natural soil	22	28
Iron ore mine tailings	18	32
Stabilized tailings	42	35

An increase in friction angle and cohesion after stabilization reflects improved shear resistance, supporting the applicability of tailings in load-bearing geotechnical systems.

5.2 Mechanical Properties of Tailings-Based Concrete

The mechanical performance of concrete mixes incorporating iron ore mine tailings was evaluated through compressive, split tensile, and flexural strength tests. Mean values from three specimens were considered for each test.

Table 8: Compressive Strength Results (MPa)

Mix ID	7 Days	28 Days	56 Days
CM (0%)	24.8	36.5	39.2
TM10	25.6	37.8	40.6
TM20	26.2	38.9	41.4
TM30	24.1	35.2	37.6
TM40	22.4	32.8	34.1

Concrete with 10–20% tailings replacement showed a 5–7% increase in 28-day compressive strength compared to the control mix, attributed to improved particle packing. Higher replacement levels resulted in strength reduction due to increased water demand and reduced workability.

Table 9: Split Tensile and Flexural Strength at 28 Days

Mix ID	Split Tensile Strength (MPa)	Flexural Strength (MPa)
CM	3.2	4.8
TM10	3.4	5.0
TM20	3.5	5.2
TM30	3.1	4.6
TM40	2.9	4.2

The trend observed in tensile and flexural strength aligns with compressive strength behavior, indicating optimal performance at moderate tailings replacement levels.

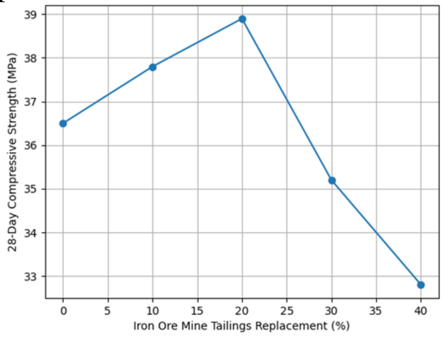

Figure 1. Effect of Iron Ore Mine Tailings Replacement on 28-Day Compressive Strength

The variation in 28-day compressive strength of concrete with different levels of iron ore mine tailings replacement is presented in Figure 1. An increase in strength was observed up to 20% replacement, which can be attributed to improved particle packing and densification of the cementitious matrix. Beyond this level, a reduction in strength occurred due to increased water demand and reduced workability

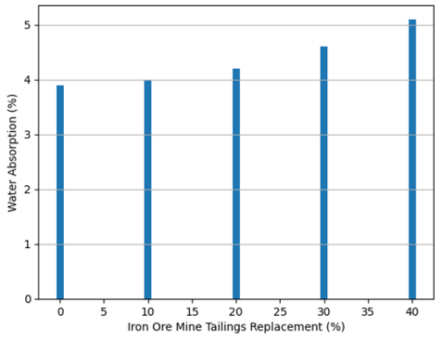

Figure 2. Effect of Iron Ore Mine Tailings on Water Absorption of Concrete

Figure 2 illustrates the variation in water absorption of concrete with increasing iron ore mine tailings content. A gradual increase in water absorption was observed with higher replacement levels, which may be attributed to the finer particle size and increased porosity associated with tailings. However, up to 20% replacement, the water absorption values remained within acceptable limits, indicating satisfactory durability performance."

5.3 Comparative Evaluation with Conventional Materials

A comparative analysis between conventional concrete and tailings-based concrete highlights the performance efficiency of iron ore mine tailings.

Table 10: Performance Comparison with Conventional Concrete

Parameter	Conventional Concrete	Tailings-Based Concrete (20%)	% Change
28-day compressive strength (MPa)	36.5	38.9	+6.6
Density (kg/m³)	2420	2385	−1.4
Water absorption (%)	3.9	4.2	+0.3

The slight increase in water absorption at higher tailings content remains within acceptable limits, while strength enhancement at optimized replacement demonstrates the feasibility of tailings as an alternative fine aggregate.

5.4 Discussion of Observed Trends

The results indicate that iron ore mine tailings significantly influence both geotechnical and concrete performance depending on replacement level and treatment method. Improved compaction and shear strength behavior support their application in geotechnical works, especially when stabilized. In concrete, fine particle size and angularity enhance packing density at lower replacement levels, leading to improved mechanical performance.

However, excessive replacement increases surface area and water demand, adversely affecting workability and strength. Statistical comparison reveals that 20% tailings replacement provides an optimal balance between strength, durability, and material efficiency. Overall, the observed trends confirm that iron ore mine tailings can be effectively utilized in civil engineering applications when appropriately proportioned and processed.

6. SUSTAINABILITY AND ENGINEERING IMPLICATIONS

The utilization of iron ore mine tailings in civil engineering applications offers significant sustainability benefits by addressing two critical challenges: the accumulation of mining waste and the depletion of natural construction resources. Replacing natural fine aggregates with iron ore tailings reduces dependence on river sand, thereby mitigating environmental degradation caused by excessive sand mining. Additionally, the reuse of tailings contributes to waste minimization by diverting large volumes of industrial by-products from tailings dams and landfills.

From an engineering perspective, the experimental results indicate that iron ore mine tailings can be effectively incorporated into concrete and geotechnical systems without compromising performance when used at optimized replacement levels. The improved compaction characteristics and shear strength behavior support their application in subgrade, embankment, and stabilized soil works. In concrete, moderate replacement levels demonstrated comparable or enhanced mechanical strength, highlighting their potential for structural and non-structural applications. These findings suggest that iron ore mine tailings can play a vital role in promoting sustainable construction practices and circular material utilization in the civil engineering sector.

7. CONCLUSIONS AND FUTURE SCOPE

7.1 Major Findings of the Study

Based on the experimental investigation and analysis conducted in this study, the following key conclusions can be drawn:

- Iron ore mine tailings exhibit favorable physical and mineralogical properties that enable their use as alternative construction materials.
- Geotechnical tests confirmed that tailings possess improved compaction characteristics and shear strength, particularly when stabilized, making them suitable for earthwork and highway applications.
- Concrete incorporating iron ore mine tailings at moderate replacement levels (10–20%) demonstrated enhanced or comparable compressive, tensile, and flexural strength relative to conventional concrete.

- Excessive replacement levels resulted in reduced performance due to increased water demand and reduced workability, emphasizing the need for optimized mix design.

7.2 Suitability of Iron Ore Mine Tailings for Construction Use

The results of this study confirm that iron ore mine tailings are technically viable for use in concrete and civil engineering applications when their inherent characteristics are adequately considered. Their compatibility with cementitious binders, acceptable mechanical performance, and favorable geotechnical behavior support their application in concrete mixtures, paving elements, stabilized soils, and embankment construction. When properly processed and proportioned, iron ore mine tailings can serve as a sustainable alternative to conventional materials, contributing to resource conservation and environmentally responsible construction practices.

7.3 Recommendations for Future Research

Although the present study demonstrates the potential of iron ore mine tailings, further research is recommended to enhance their practical implementation:

- Long-term durability studies, including resistance to chemical attack, freeze–thaw cycles, and chloride penetration, should be conducted.
- Field-scale trials are necessary to validate laboratory findings and assess performance under real construction conditions.
- Advanced treatment and activation techniques may be explored to improve reactivity and bonding characteristics of tailings.
- Environmental impact assessments, including leachability and life-cycle analysis, should be undertaken to ensure long-term sustainability and regulatory compliance.

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Conflict of Interest:

Authors here by declared that, there is no conflict of interest.

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