



Comparative Assessment of Alternative Fine Aggregates for Sustainable Concrete: Physical, Chemical and Mechanical Characterization of Sri Lankan Sands

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ABSTRACT

The over-extraction of river sand in Sri Lanka has reduced alluvial reserves in major basins by over 40% between 2010 and 2023, highlighting an urgent need for sustainable alternatives. This study presents the first comprehensive comparative analysis of four distinct sand types- river (Polonnaruwa), sea (Muthurajawela), dune (Kandakuliya), and estuary (Kalutara)-using integrated physical, chemical, and mechanical evaluation. Tests included sieve analysis, chloride content measurement via Volhard's method, and strength assessments at 7 and 28 days. Results showed that river and dune sands achieved compressive strengths exceeding 30 MPa and contained low chloride levels (<500 mg.kg⁻¹), aligning with international standards for structural concrete. Although sea sand's chloride content was high (1,796 mg.kg⁻¹, 259% above limit), it could be viable if properly treated. Estuary sand reached 29.3 MPa strength but had borderline chloride levels, restricting its application. Failure mode analysis indicated strong structural performance for river and dune sands, whereas sea and estuary sands exhibited brittle failure patterns. Overall, processed dune sand and treated sea sand are promising substitutes for river sand, promoting sustainability. Ensuring chloride regulation and advancing treatment technologies are essential for successful adoption.

1. INTRODUCTION

The introduction provides a comprehensive overview of sand usage in construction, highlighting both environmental and engineering considerations. It begins by framing the global and national issues of unsustainable river sand extraction and then narrows its focus to the pressing challenges faced by Sri Lanka. The following sections detail the environmental crisis caused by excessive mining and identify the research gap that this study aims to fill.

1.1. Environmental Crisis from River Sand Mining

Worldwide, the production of concrete annually consumes over 50 billion tons of sand, with river sand being the preferred fine aggregate due to its optimal gradation and low impurity content (Koehnken & Rintoul 2018). In Sri Lanka, rapid construction growth has led to increased river sand extraction, causing severe environmental damage such as riverbed degradation, bank erosion, habitat destruction, and heightened flood risks (Dias et al. 2008). The Deduru Oya basin highlights this crisis, where sand mining has reduced sediment loads by 40%, thereby accelerating coastal erosion (United Nations Environment Program 2019). The UNEP recognizes sand mining as a vital sustainability issue, with Sri Lanka

ranked among the top ten countries facing significant riverine ecosystem collapse. Moreover, the scarcity of river sand has driven up construction costs, adversely impacting housing affordability and infrastructure development (Dolage et al. 2013). While government regulations aimed at restricting extraction are environmentally essential, they have also limited supply and increased the urgency for sustainable alternatives (Mahendran et al. 2016).

1.2. Research Gap and Objectives

Although previous studies have explored individual alternatives such as manufactured sand and offshore sand, a comprehensive comparative analysis of Sri Lanka's diverse sand resources remains limited. Dias et al. (2008) established safe chloride limits (0.075% by weight) for offshore sand, while Ratnayake et al. (2014) demonstrated the potential of sea sand with proper washing. However, a systematic evaluation of multiple sand types from different geographical sources is lacking in thorough documentation.

Recent international research has investigated various alternative aggregates. Cepuritis et al. (2014) found that manufactured sand with optimized particle packing enhanced concrete strength by 15% compared to natural sand. Kumar et al. (2025) conducted experimental analysis showing that refractory brick can serve as a sustainable substitute for natural fine aggregates in concrete. In coastal regions, desalinated sea sand has shown promise; Zhao et al. (2019) achieved chloride reductions of 85% through electrochemical treatment. Similarly, desert sand utilization has gained attention, with Benabed et al. (2014) reporting that dune sand blended with 30% crushed aggregate achieved compressive strengths exceeding 35 MPa.

Nonetheless, a systematic comparison of multiple sand types within a single geographical context, especially for tropical island nations like Sri Lanka, remains underexplored. Previous Sri Lankan studies have examined individual alternatives: Dias et al. (2008) established safe chloride limits (0.075% by weight) for offshore sand, and Ratnayake et al. (2014) showed sea sand potential with proper washing. However, a comprehensive analysis comparing diverse geological sources is still lacking.

This study aims to address this gap through a systematic, integrated evaluation of four Sri Lankan sand types, combining physical-chemical characterization with mechanical performance and economic analysis within a unified framework. While individual alternatives have been studied in isolation, our contribution lies in the direct comparative assessment, enabling evidence-based material selection for specific applications. Our objectives were to:

1. Characterize the physical and chemical properties of river, sea, dune, and estuary sands.
2. Evaluate concrete performance using these sands through strength testing.
3. Establish correlations between sand properties and concrete behavior.
4. Identify sustainable alternatives meeting engineering and environmental criteria.

2. MATERIALS AND METHODS

This section details the experimental framework established to meet the research objectives. It outlines the sources of raw materials, the procedures used for sampling and preparation, and the testing protocols followed. Standardized methods and internationally accepted guidelines were applied to ensure reproducibility, accuracy, and comparability of results. The overall strategy combines both field sampling and laboratory assessments, enabling a thorough evaluation of the material properties pertinent to the study.



Fig. 1: Sample collection locations across Sri Lanka show the geographical distribution of river sand (Polonnaruwa), dune sand (Kandakuliya), estuary sand (Kalutara), and sea sand (Muthurajawela) sources.

Table 1: Materials' physical properties.

| Material | Property | Value | Standard |
|------------------------------------|--------------------------|-------------------------------|-------------|
| Ordinary Portland Cement (OPC) | Specific gravity | 3.15 | BS EN 196-6 |
| | Initial setting time | 145 min | BS EN 196-3 |
| | 28-day strength | 53.2 MPa | BS EN 196-1 |
| Coarse Aggregate (Crushed granite) | Specific gravity | 2.68 | BS 812-2 |
| | Water absorption | 0.85% | BS 812-2 |
| | Aggregate crushing value | 18.2% | BS 812-110 |
| | Nominal size | 20 mm | - |
| All sands | Specific gravity | 2.45–2.68 | BS 812-2 |
| | Water absorption | 0.5–2.3% | BS 812-2 |
| | Bulk density | 1,420–1,650 kg.m ³ | ASTM C29 |

2.1. Sample Collection and Preparation

We collected representative sand samples from four distinct geographical regions across Sri Lanka to ensure diversity and resource potential (Fig. 1). River sand was sourced from Polonnaruwa, dune sand from Kandakuliya in the Puttalam District, estuary sand from Kalutara, and filtered sea sand from Muthurajawela. Field samples were collected following USGS protocols, sampling at least 500 m from human settlements using stratified random sampling within 10 m² grids. Bulk samples were taken from horizons at depths of 0.3 to 0.5 m and stored in HDPE containers. Commercial sands were obtained from ISO 9001:2015 certified suppliers with verified geological source coordinates. To reflect practical field-scale behavior rather than idealized laboratory conditions, bulk material quantities were used throughout testing, aligning with construction industry practices that account for batch-to-batch variations and larger sample volumes during quality control. For sieve analyses and chemical testing, representative sub-samples were extracted via quartering methods to ensure statistical validity while testing manageable quantities.

Sample preparation involved oven-drying at 105°C for 2 h, followed by quartering to obtain representative test portions. Total sample requirements were calculated based on standardized testing protocols, ensuring sufficient material for all planned analyses. Table 1 presents the physical properties of the materials used.

2.2. Physical Characterization

Physical characterization was conducted to evaluate the fundamental properties of the collected sand samples prior to their incorporation into concrete mixes. The analyses focused on particle size distribution and chemical composition, as these parameters critically influence the workability, durability, and mechanical performance of concrete. Standardized procedures were adopted to ensure

comparability across different sand sources and alignment with international specifications. The following subsections detail the methodologies employed.

2.2.1. Sieve Analysis

Particle size distribution was determined using the BS 812: Part 1 (1995) methodology. Dried samples (300 g) were passed through a series of standard sieves (2 mm to 0.063 mm) using manual shaking for 5 min per sieve. The fineness modulus was calculated, and the gradation was compared with BS EN 12620:2013 limits.

2.2.2. Chemical Analysis

Chloride content was determined using Volhard's argentometric method in accordance with ASTM C1218/ C1218M (2020). Standard 0.1 N AgNO₃ and KSCN solutions were prepared, and 10 g sand samples were titrated using ferric alum as the indicator. Chloride content was calculated using Equation 01.

$$\text{Cl}^- (\text{mg.kg}^{-1}) = \frac{[(V_1 - V_2) \times N(\text{KSCN}) \times 35.45 \times 1000]}{m(\text{sample})} \quad \dots(1)$$

where:

V_1 = volume of AgNO₃ solution added (mL)

V_2 = volume of KSCN solution used in back-titration (mL)

$N(\text{KSCN})$ = normality of potassium thiocyanate solution

$m(\text{sample})$ = mass of sand sample (g)

35.45 = atomic weight of chlorine (g.mol⁻¹)

2.3. Concrete Performance Testing

We prepared Grade 30 concrete using standardized mix proportions (cement: 380 kg.m³, water–cement ratio: 0.50) for each sand type. Ordinary Portland Cement and crushed granite coarse aggregate were kept constant across all mixes.

Mix proportions were determined using the BRE method (Building Research Establishment 1997). The composition per cubic meter was as follows: Ordinary Portland Cement (CEM I 42.5N), 380 kg; fine aggregate (test sands), 720 kg; coarse aggregate (crushed granite, 20 mm), 1,050 kg; and water, 190 L (water–cement ratio: 0.50). No admixtures were used in the control mixes to maintain consistency across sand types. However, variations in fineness modulus (Table 2) may have influenced the optimum mix proportions. This limitation is discussed in Section 4.3.

Mixing was carried out using a 100 L pan mixer in accordance with BS EN 12390-2:2019. Dry materials were mixed for 2 min, followed by the gradual addition of water over 1 minute, and then 3 min of wet mixing. Slump was maintained at 75–100 mm for all mixes to ensure consistent workability.

2.3.1. Compressive Strength

Following the BS EN 12390-2:2019 standard, we cast 150 mm³ cubes using steel molds, vibrated them to ensure uniform compaction, and cured them in lime-saturated water. Testing was performed at 7 and 28 days with an ELE ADR-Auto 3000 kN machine, applying a loading rate of 0.6 MPa.s⁻¹.

2.3.2. Tensile Strength

We prepared cylindrical specimens (90 mm diameter × 180 mm height) per ASTM C496/C496M-17. After curing, specimens underwent splitting tension tests at 0.04 MPa.s⁻¹ loading rate. Tensile strength was calculated using equation 02.

$$f_t = 2P_{\max}/(\pi ld) \quad \dots(2)$$

where:

f_t = splitting tensile strength (MPa)

P_{\max} = maximum applied load at failure (N)

l = length of cylinder (mm)

d = diameter of cylinder (mm)

2.4. Quality Assurance

All tests included triplicate analyses, with a coefficient of variation under 5% considered acceptable. Statistical analysis was performed using 95% confidence intervals, and Grubbs' test was applied to identify outliers. Laboratory conditions were maintained at 20°C ± 2°C throughout the testing process.

3. RESULTS AND DISCUSSION

The following section presents the experimental findings and their interpretation in relation to the study objectives. The results are organized to highlight the physical and chemical characterization of the sand samples, followed by an evaluation of their influence on concrete performance. Comparisons with relevant standards and published literature are incorporated to contextualize the outcomes and assess practical implications.

3.1. Sand Characterization

Sand characterization was carried out to establish the baseline material properties prior to concrete production. Both physical and chemical properties were examined to assess compliance with construction standards and to anticipate potential effects on strength and durability. The subsequent subsections describe the particle size distribution and chloride content of the sand types studied.

3.1.1. Particle Size Distribution

Sieve analysis revealed distinct gradation patterns among the sand types (Table 2, Fig. 2). River sand exhibited a well-graded distribution (Fineness Modulus = 2.8), meeting BS EN 12620:2013 requirements. Sea sand showed a higher fine

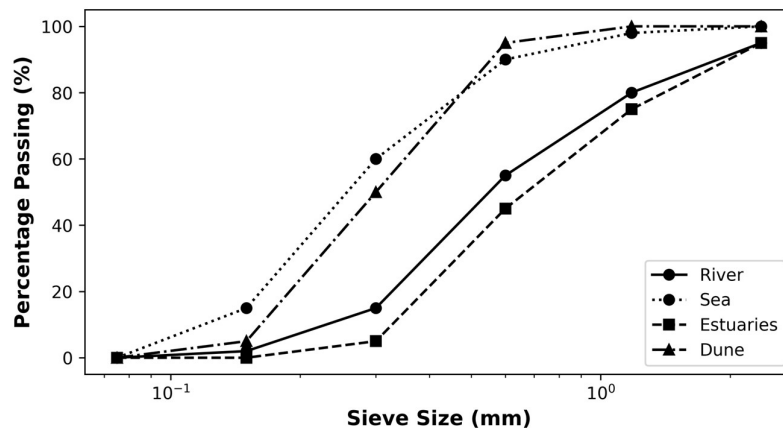


Fig. 2: Particle size distribution curves for all four sand types showing the gradation differences.

Table 2: Particle Size Distribution and Fineness Modulus.

| Sand Type | Fineness Modulus | Gradation Compliance | Key Characteristics |
|-----------|------------------|----------------------|----------------------------|
| River | 2.8 | Full compliance | Well-graded, minimal fines |
| Sea | 1.9 | Excessive fines | High 0.25 mm fraction |
| Dune | 2.3 | Marginal | Uniform requires blending |
| Estuary | 2.1 | Poor | Bimodal distribution |

content, particularly in the 0.25 mm and 0.063 mm fractions, while estuary sand displayed a bimodal distribution with significant material retained on the 1 mm and 0.5 mm sieves.

River sand demonstrates ideal gradation, while sea sand shows excessive fines, dune sand presents uniform distribution, and estuary sand exhibits bimodal characteristics.

Dune sand presented uniform gradation but required blending with coarser material to optimize packing density. The gradation affects concrete workability and strength development, with well-graded sands producing superior performance.

3.1.2. Chemical Analysis

Chloride content varied considerably among different sand types, directly influencing the durability of concrete (Table 3, Fig. 3). River sand exhibited excellent compliance, with a chloride level of 179 mg.kg^{-1} , which is 64% below the permissible limit. Dune sand also met the required standards at 215 mg.kg^{-1} , posing minimal risk of corrosion. The bar

Table 3: Chloride content analysis.

| Sand Type | Chloride Content [mg.kg^{-1}] | BS 8500-1:2023 Limit | Compliance Status |
|-----------|--|----------------------|-------------------|
| River | 179 ± 5.5 | 500 | Excellent |
| Sea | $1,796 \pm 7.5$ | 500 | Exceeds by 259% |
| Dune | 215 ± 5.5 | 500 | Good |
| Estuary | 431 ± 1.5 | 500 | Borderline |

chart clearly demonstrates that sea sand has an excessive chloride content, necessitating proper treatment.

The sea sand significantly exceeded permissible limits at $1,796 \text{ mg.kg}^{-1}$, necessitating extensive desalination treatment. The estuary sand approached the safety threshold at 431 mg.kg^{-1} , indicating that blending or washing procedures are required for safe utilization.

3.2. Concrete Performance

Results on concrete performance are provided to evaluate how different sand types influence the structural properties of Grade 30 mixes. The focus is on strength-related parameters, which are vital for determining load-bearing capacity and durability in structural elements. The analysis begins with the development of compressive strength, followed by an assessment of tensile performance, offering a thorough understanding of the mechanical behavior.

3.2.1. Strength Development

Compressive strength results clearly distinguished the performance of different sand types (Table 4, Figs. 4(a) and 4(b)). River sand demonstrated outstanding 28-day strength

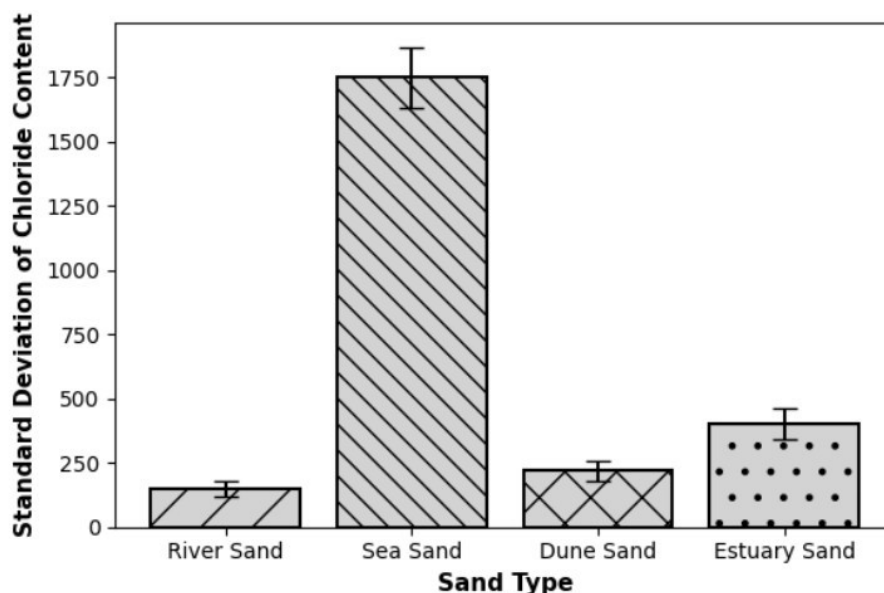


Fig. 3: Chloride content comparison across sand types with BS 8500-1:2023 permissible limit (500 mg.kg^{-1}).

Table 4: 28-Day Compressive (MPa)^a.

| Sand Type | 28-Day Compressive (MPa) | 28-Day Tensile (MPa) | Grade 30 Compliance | Failure Mode |
|-----------|--------------------------|----------------------|---------------------|--------------|
| River | 34.2 ± 1.2 | 3.4 ± 0.15 | Yes | Conical |
| Sea | 27.5 ± 2.1 | 2.3 ± 0.25 | No | Shear |
| Dune | 31.8 ± 1.5 | 3.1 ± 0.20 | Yes | Splitting |
| Estuary | 29.3 ± 1.8 | 2.7 ± 0.18 | No | Delamination |

(34.2 MPa), surpassing Grade 30 standards, with a typical conical failure pattern indicating strong structural integrity.

Values with different superscript letters differ significantly ($p < 0.05$, Tukey HSD test). River sand: A; Dune sand: AB; Estuary sand: B; Sea sand: B (Ferraris 2001).

Dune sand exhibited marginal compliance at 31.8 MPa despite its fine particle size, with angular grains potentially enhancing packing density. The splitting failure mode indicated high internal tensile stresses, likely resulting from particle interlock, gradation effects, or workability differences during casting. This mode remained structurally acceptable for Grade 30 applications.

SEA sand performed significantly worse at 27.5 MPa, aligning with known issues of chloride-induced microcracking and poor aggregate-cement bonding reported in literature (Ramana 2017, Zhao et al. 2019). Although direct microstructural analysis was not performed, shear failure patterns suggested brittle behavior, influenced by chloride content, gradation, and workability, rather than sand type alone. Without treatment, the concrete is unsuitable for structural use.

Estuary sand fell short of Grade 30 requirements at 29.3 MPa, possibly due to bimodal gradation creating voids and weak planes. The delamination failure pattern observed is

consistent with an inhomogeneous microstructure, though further characterization is necessary to confirm this. The graph indicates river sand achieving the highest strength, followed by dune sand meeting Grade 30 at 30 MPa, while sea and estuary sands do not meet the standard.

The superior performance of river sand aligns with established literature on optimal gradation and particle morphology (Ferraris 2001). Its well-graded distribution ($FM = 2.8$) promotes efficient particle packing, reduces void content, and enhances cement–aggregate bonding. The comparatively strong performance of dune sand, despite its finer particles, can be attributed to angular grain morphology resulting from aeolian weathering processes, which increases mechanical interlock (Rashad 2020).

The underperformance of sea sand is likely associated with chloride-induced effects during cement hydration, as documented by Ramana (2017). Literature suggests that excessive Cl^- ions can interfere with C–S–H gel formation and promote the formation of expansive ettringite within the interfacial transition zone. However, these mechanisms were not directly verified through microstructural analysis in the present study. The observed shear failure mode indicates reduced ductility, which is a critical concern for seismic applications.

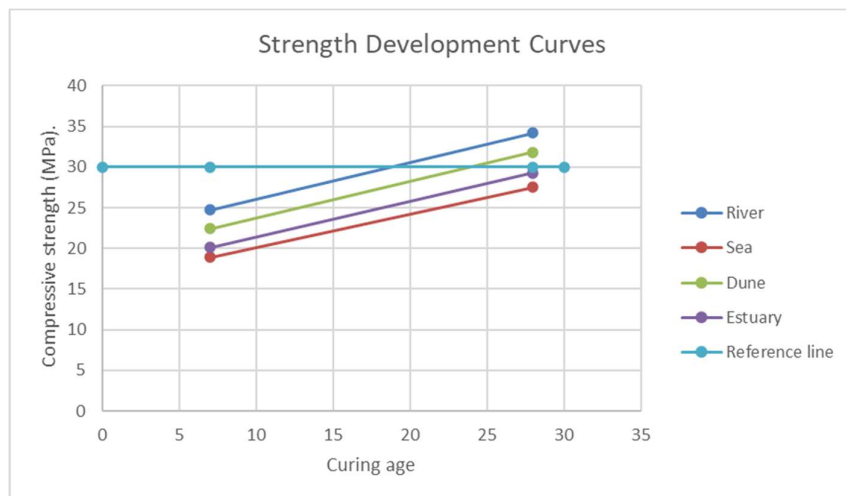


Fig 4(a): Compressive strength development over time (7 and 28 days) for concrete made with different sand types.

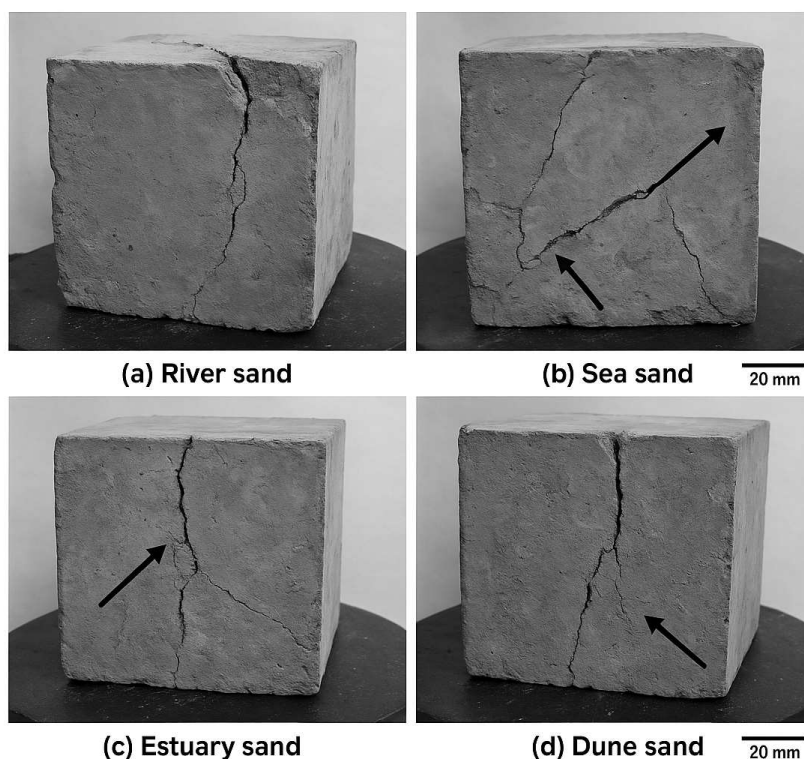


Fig. 4(b): Failure mode comparison of 150 mm concrete cubes at 28 days: (a) River sand showing conical failure with intact edges, (b) Sea sand exhibiting sudden shear plane with explosive spalling, (c) Dune sand displaying diagonal splitting at 45° angle.

Estuary sand exhibited marginal performance, which may be attributed to its complex mineralogy and bimodal gradation. The gap-graded distribution creates localized weak zones, where insufficient fine material fails to fill voids between coarse particles. This phenomenon, often referred to as particle segregation, reduces homogeneity and creates preferential crack propagation paths (Brouwers & Radix 2005).

Statistical Analysis: One-way ANOVA was performed to evaluate significant differences in compressive strength among sand types ($\alpha = 0.05$). The analysis revealed statistically significant differences ($F(3,8) = 45.2, p < 0.001$). Post-hoc Tukey HSD tests confirmed that:

- River sand strength significantly exceeded sea sand ($p < 0.001$) and estuary sand ($p = 0.002$)
- Dune sand showed no significant difference from river sand ($p = 0.089$)
- Sea sand and estuary sand were not significantly different ($p = 0.312$)

Given the sample size ($n=3$ per sand type), results should be interpreted with appropriate caution. While differences with $p < 0.01$ demonstrate robust statistical significance, comparisons approaching borderline significance (e.g.,

river vs. dune sand, $p = 0.089$) warrant validation through larger-scale studies before definitive conclusions. The observed effect sizes and consistency with physical property measurements support the reported trends, though expanded sampling would strengthen confidence intervals.

3.2.2. Tensile Performance

Splitting tensile strength correlated with compressive performance, with river sand achieving optimal results (3.4 MPa) as shown in Fig. 5. The tensile-to-compressive strength ratios ranged from 0.08 to 0.10, aligning with established empirical relationships for normal-weight concrete.

The scatter plot illustrates a clear linear relationship, with river and dune sands demonstrating superior performance across both parameters.

3.3. Sustainability Assessment

This assessment combines technical performance with environmental and economic factors to determine the viability of alternative sands for large-scale use. It extends beyond laboratory strength tests to include considerations of resource depletion, processing energy requirements, and lifecycle costs. The following sections analyze environmental impact, economic feasibility, and overall performance ranking.

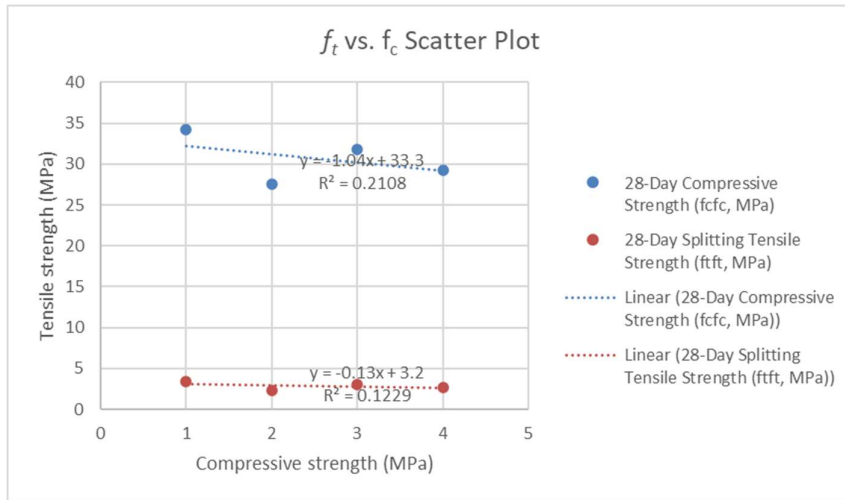


Fig. 5: Correlation between compressive and tensile strengths for all sand types.

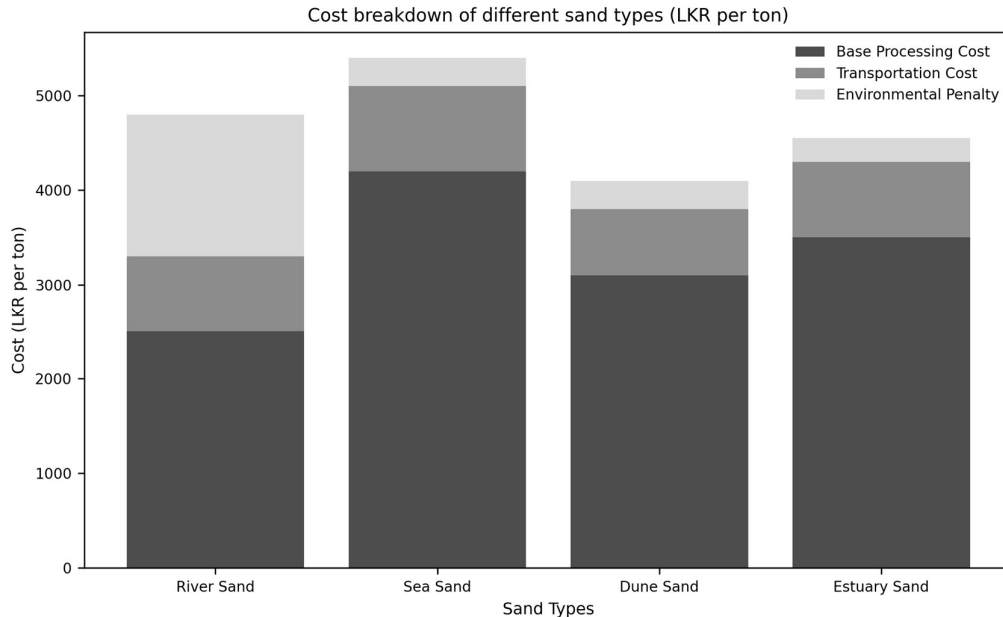


Fig. 6: Comparative cost analysis showing estimated total cost per ton, including processing, transportation, and modeled environmental externalities (based on carbon-equivalent ecosystem service valuation).

3.3.1. Environmental Impact

A comparative analysis shows that alternative sands vary in their processing needs, which affects energy consumption and resource use. Dune sand requires minimal processing beyond grading, whereas sea sand involves substantial desalination infrastructure.

3.3.2. Economic Analysis

Comparative cost analysis, including hypothetical environmental externality pricing, suggests that dune sand (processing cost: LKR 3,100.ton⁻¹) may provide economic

advantages over continued river sand extraction. Sea sand processing requires higher capital investment for desalination infrastructure, offset by abundant coastal availability. Fig. 6 presents the economic comparison, including processing costs, transportation, and environmental impact penalties (Ramana 2017).

Cost data were obtained through market surveys of three certified suppliers in each region (n=12 total) during August-September 2024. Processing costs include washing, sieving, and quality control testing. Transportation costs are assumed

to be 50 km average distance to Colombo construction sites at LKR 15.ton⁻¹.km⁻¹. Environmental externalities were estimated using carbon pricing equivalent (LKR 2,500. ton⁻¹ CO₂) as a proxy for ecosystem service valuation for riverbed disruption (Costanza 2014). These values represent comparative scenarios rather than precise economic costs, intended to illustrate relative sustainability trade-offs. Desalination costs for sea sand include electrochemical treatment infrastructure amortized over a 10-year operational lifespan.

3.4. Performance Ranking

Based on combined technical, environmental, and economic criteria as illustrated in Fig. 7:

- i. River sand (reference standard, environmental concerns)
- ii. Dune sand (best overall alternative)
- iii. Estuary sand (limited applications)
- iv. Sea sand (requires extensive treatment)

4. PRACTICAL APPLICATIONS AND RECOMMENDATIONS

This section translates the experimental findings into practical guidelines and policy measures aimed at enhancing sustainable sand utilization in the Sri Lankan construction sector. The recommendations are structured to address both immediate implementation strategies at the material and project level, as well as broader regulatory and economic frameworks that can ensure long-term adoption.

4.1. Implementation Guidelines

Implementation guidelines focus on the practical adaptation of different sand types for construction use. Each category of sand is considered separately to highlight specific limitations, required treatments, and optimization strategies, ensuring that materials are applied effectively while maintaining structural safety and durability.

4.1.1. Dune Sand

Dune sand can be made suitable for structural concrete with minor modifications, such as blending with 20% crushed coarse sand to optimize gradation, using 0.5% polycarboxylate superplasticizers to improve workability, and monitoring the fineness modulus during batching.

4.1.2. Sea Sand

Sea sand, however, requires comprehensive treatment before use, including electrochemical desalination to reduce chloride levels below 500 mg/kg, aging for 60–90 days under controlled conditions, and blending with 30% manufactured sand to enhance gradation.

4.1.3. Estuary Sand

Based on sub-threshold compressive strength (29.3 MPa) and borderline chloride content (431 mg.kg⁻¹), estuary sand should be strictly limited to non-structural applications only. Acceptable uses include plastering mortars, non-load-bearing blockwork, and screeds, provided pre-washing reduces chloride content by a minimum of 40–50% and batch testing confirms compliance below 400 mg/kg. Use in structural elements, including reinforced masonry or load-bearing walls, is not recommended based on the current characterization data.

4.2. Policy Recommendations

Beyond project-level applications, broader policy interventions are necessary to institutionalize safe and sustainable sand usage. Recommendations in this section target regulatory frameworks and economic measures, with the aim of encouraging compliance, promoting innovation, and reducing reliance on untreated natural sand resources.

4.2.1. Regulatory Framework

To support safe and sustainable sand usage, policy recommendations include enforcing chloride testing requirements for all construction sands, banning untreated sea sand in reinforced concrete applications, and establishing quality standards for alternative sand processing.

4.2.2. Economic Incentives

Economic incentives such as subsidizing sand washing facilities in coastal regions, providing tax benefits for contractors using more than 50% alternative sands, and supporting research and development of sand treatment technologies are recommended.

4.3. Study Limitations and Future Research

While this study provides valuable insights into Sri Lankan alternative sands, several limitations should be acknowledged:

1. **Durability Assessment:** Long-term durability parameters, including chloride penetration resistance, sulfate attack resistance, and freeze–thaw performance, were not evaluated. Future studies should incorporate accelerated aging tests in accordance with ASTM C1202 and BS 1881-124 (ASTM C33/C33M-18 2018).
2. **Microstructural Analysis:** The absence of SEM/EDS or XRD analysis limits understanding of interfacial transition zones and hydration product formation. Advanced microscopy techniques would help elucidate performance mechanisms (Shetty 2019, Neville 2011, Mindess 2003).

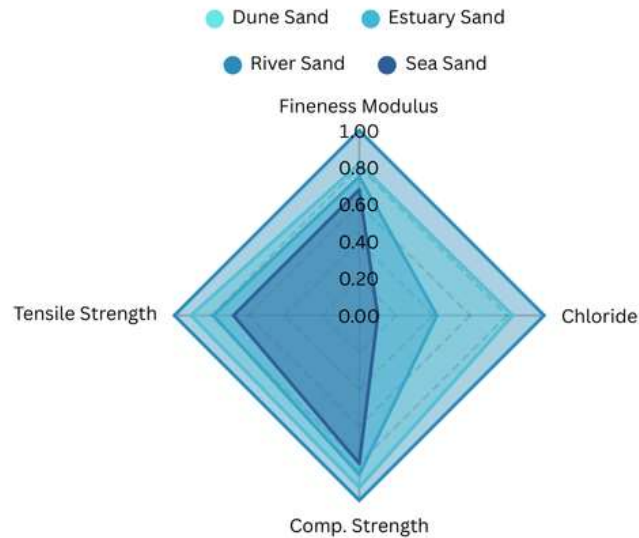


Fig. 7: Multi-criteria performance radar chart comparing all sand types across five parameters: compressive strength, tensile strength, chloride compliance, gradation quality, and environmental sustainability. Dune sand shows the most balanced profile as a river sand alternative.

3. **Blending Optimization:** A systematic investigation of blend proportions (e.g., 70% dune sand + 30% crushed sand) could optimize gradation and performance beyond single-source applications.
4. **Economic Data:** The cost analysis was based on market surveys rather than a controlled life-cycle assessment. Comprehensive economic modeling, including carbon footprint analysis, is recommended.
5. **Sample Diversity:** Single-source sampling for each sand type may not adequately capture regional variability. Multi-site sampling would strengthen the generalisability of the findings. Future research should prioritize:
 - (a) five-year durability monitoring of field structures,
 - (b) development of rapid chloride removal protocols, and
 - (c) standardization of alternative sand specifications within Sri Lankan codes.
6. **Mix Design Variables:** This study maintained a constant fine aggregate content (720 kg.m^{-3}) across all sand types to reflect common field practice, where aggregate substitution is typically performed on a volumetric basis. However, differences in fineness modulus (2.8–1.9) and gradation among sand types represent confounding variables that may have influenced workability and strength independently of intrinsic material properties. While this approach enhances practical relevance, future studies should investigate optimized mix proportions for each sand type (adjusting fine-to-coarse ratios and water content) to isolate material effects from mix design variables. Additionally, maintaining a constant

slump (75–100 mm) may have masked differences in water demand associated with particle shape and specific surface area.

5. CONCLUSIONS

This comprehensive evaluation confirms that Sri Lankan alternative sands can effectively replace river sand in concrete production when properly characterized and processed. Key findings indicate that dune sand is technically viable for structural concrete, achieving a 31.8 MPa compressive strength with a chloride content of 215 mg.kg^{-1} and requiring minimal processing. Although river sand offers slightly higher strength at 34.2 MPa, it faces sustainability challenges due to environmental concerns. Sea sand shows promise after desalination, which significantly reduces its initial chloride content of $1,796 \text{ mg.kg}^{-1}$ to acceptable levels. Estuary sand, with moderate performance, is best suited for non-structural applications. Adopting alternative sands can alleviate pressure on river ecosystems while maintaining construction quality. Dune sand and processed estuary sand emerge as the most balanced options regarding performance, sustainability, and economic feasibility. Successful implementation depends on regulatory enforcement, the development of processing facilities, and industry training, with phased adoption in non-critical applications helping to build confidence and technical expertise. Future research should focus on assessing long-term durability, optimizing blending ratios, and improving cost-effective treatment technologies. These efforts will lay the groundwork for sustainable construction policies that support Sri Lanka's infrastructure development while protecting natural ecosystems.

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