

Original Research

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

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ABSTRACT

Excessive River sand extraction in Sri Lanka has depleted over 40% of alluvial reserves in major basins (2010-2023), necessitating urgent identification of sustainable alternatives. This study provides the first integrated comparative assessment of four geographically distinct sand types, river (Polonnaruwa), sea (Muthurajawela), dune (Kandakuliya), and estuary (Kalutara) through integrated physical, chemical, and mechanical characterization. Sieve analysis, chloride determination (Volhard's method), and strength testing at 7 and 28 days were conducted. River and dune sands achieved compressive strengths above 30 MPa with low chloride content (<500 mg/kg), meeting international standards for structural concrete. Sea sand exceeded chloride limits (1,796 mg/kg; 259% higher) but showed potential if treated. Estuary sand reached 29.3 MPa with borderline chloride levels, limiting its use. Failure analysis indicated good structural performance with river and dune sand, while sea and estuary sands showed brittle modes. Overall, processed dune sand and treated sea sand offer viable replacements for river sand, supporting sustainability. Successful implementation requires chloride regulation and investment in treatment technologies.

INTRODUCTION

The introduction outlines the broader context of sand utilization in construction, emphasizing both environmental and engineering perspectives. It begins by situating the problem of unsustainable river sand extraction within global and national scales, before narrowing the discussion to Sri Lanka's pressing challenges. The subsequent subsections elaborate on the environmental crisis stemming from excessive mining and highlight the research gap this study seeks to address.

1.1 Environmental Crisis from River Sand Mining

Concrete production worldwide consumes over 50 billion tons of sand annually, with river sand being the preferred fine aggregate due to its optimal gradation and low impurity content (KoeHNken and Rintoul, 2018). In Sri Lanka, rapid construction growth has intensified river sand extraction, causing irreversible environmental damage including riverbed degradation, bank erosion, habitat destruction, and increased flood vulnerability (Dias et al, 2008).

The Deduru Oya basin exemplifies this crisis, where sand mining reduced sediment loads by 40%, accelerating coastal erosion rates (United Nations Environment Programme, 2019). The United Nations Environment Programme identifies sand mining as a critical sustainability challenge, with Sri Lanka ranking among the top 10 countries facing severe riverine ecosystem collapse.

Beyond environmental impacts, river sand scarcity has inflated construction costs, affecting housing affordability and infrastructure development (Dolage, Dias, and Ariyawansa, 2013). Government regulations restricting extraction, while environmentally necessary, have further constrained supply and heightened the need for viable alternatives (Mahendran, Jayasinghe, and Perera, 2016).

1.2 Research Gap and Objectives

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

Recent international research has explored various alternative aggregates. Cepuritis et al. (Cepuritis et al, 2014) demonstrated that manufactured sand with optimized particle packing improved concrete strength by 15% compared

to natural sand. Kumar et al has been experimentally analyzed that sustainable concrete made with refractory brick as a substitute of natural fine aggregates (Kumar et al, 2025). In coastal regions, desalinated sea sand has shown promise, with Zhao et al. (Zhao et al, 2019) achieving chloride reductions of 85% through electrochemical treatment. Similarly, desert sand utilization has gained attention; Benabed et al. (Benabed et al, 2014) reported that dune sand blended with 30% crushed aggregate achieved compressive strengths exceeding 35 MPa. However, systematic comparison of multiple sand types within a single geographical context, particularly for tropical island nations like Sri Lanka, remains underexplored. Previous Sri Lankan studies have examined individual alternatives, Dias et al. established safe chloride limits (0.075% by weight) for offshore sand, while Ratnayake et al. (Ratnayake et al, 2014) demonstrated sea sand potential with proper washing, but comprehensive comparative analysis across diverse geological sources is lacking.

This study addresses this gap through 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 that enables evidence-based material selection for specific applications. Our objectives were to:

1. Characterize 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. METHODS

This section outlines the experimental framework designed to achieve the research objectives. It describes the sources of raw materials, procedures adopted for sampling and preparation, and subsequent testing protocols. Standardized methods and internationally recognized guidelines were employed to ensure reproducibility, accuracy, and comparability of results. The overall approach integrates both field sampling and laboratory-based assessments, allowing for a comprehensive evaluation of material properties relevant to the study.

2.1 Sample Collection and Preparation

We collected representative sand samples from four geographical sources across Sri Lanka, ensuring diversity and resource potential (Fig. 1). We sourced river sand from Polonnaruwa, dune sand from Kandakuliya (Puttalam District), estuary sand from Kalutara, and filtered sea sand from Muthurajawela. For field samples, we followed USGS protocols, sampling ≥ 500 m from human settlements using stratified random sampling across 10 m^2 grids. We extracted bulk samples from 0.3-0.5 m depth horizons and stored them in HDPE containers. Commercial sands were procured from ISO 9001:2015 certified suppliers with verified geological source coordinates. Bulk material quantities were used throughout testing to ensure results reflected practical field-scale behavior rather than idealized laboratory conditions. This approach aligns with construction industry practices where batch-to-batch variations and larger sample volumes are inherent to quality control procedures. For sieve analysis and chemical testing, representative sub-samples were extracted using quartering methods to maintain statistical validity while testing manageable quantities.

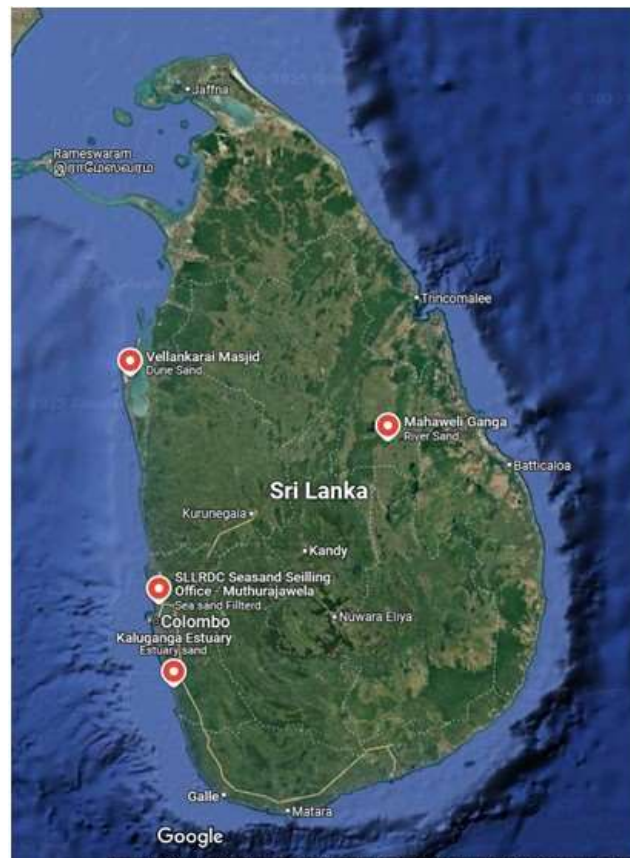


Fig 1. Sample collection locations across Sri Lanka showing the geographical distribution of river sand (Polonnaruwa), dune sand (Kandakuliya), estuary sand (Kalutara), and sea sand (Muthurajawela) sources.

Table 01: 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

Sample preparation involved oven-drying at 105°C for 2 hours and 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 shows the physical properties of the materials used.

2.2 Physical Characterization

Physical characterization was undertaken 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 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 specific methodologies employed.

2.2.1 Sieve Analysis

We determined particle size distribution using BS 812: Part 1 (1995) methodology. We passed dried samples (300 g) through standard sieves (2 mm to 0.063 mm) with manual shaking for five minutes per sieve. We calculated fineness modulus and compared gradation with BS EN 12620:2013 limits.

2.2.2 Chemical Analysis

We determined chloride content using Volhard's Argentometric method following ASTM C1218/C1218M (2020). We prepared 0.1 N AgNO₃ and KSCN solutions, then titrated 10 g sand samples with ferric alum indicator. Chloride content was calculated using below equation 01.

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

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)

2.3 Concrete Performance Testing

We prepared Grade 30 concrete using standardized mix proportions (cement: 380 kg/m³, water-cement ratio: 0.50) with 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) with the following composition per cubic meter: Ordinary Portland Cement (CEM I 42.5N): 380 kg, Fine aggregate (test sands): 720 kg, Coarse aggregate (crushed granite, 20 mm): 1,050 kg, Water: 190 L (water-cement ratio: 0.50). No admixtures were used in control mixes to maintain consistency across sand types, though variations in fineness modulus (Table 2) may have influenced optimal mix proportions. This limitation is discussed in Section 4.3. Mixing was performed in a 100 L pan mixer following BS EN 12390-2:2019 procedures: dry materials mixed for 2 minutes, water added gradually over 1 minute, followed by 3 minutes of wet mixing. Slump was maintained at 75-100 mm for all mixes to ensure consistent workability.

2.3.1 Compressive Strength

Following BS EN 12390-2:2019, we cast 150 mm³ cubes in steel molds, vibrated them for uniform compaction, and cured them in lime-saturated water. We conducted testing at 7 and 28 days using an ELE ADR-Auto 3000 kN machine at 0.6 MPa/s loading rate.

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 loading rate. Tensile strength was calculated using equation 02.

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

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 <5% deemed acceptable. We conducted statistical analysis using 95% confidence intervals and applied Grubbs' test for outlier detection. Laboratory conditions were maintained at 20°C ± 2°C throughout testing.

3 FINDINGS AND DISCUSSION

The following section presents the experimental findings and their interpretation in relation to the study objectives. Results are organized to highlight the physical and chemical characterization of 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 attributes 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 studied sand types.

3.1.1 Particle Size Distribution

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

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

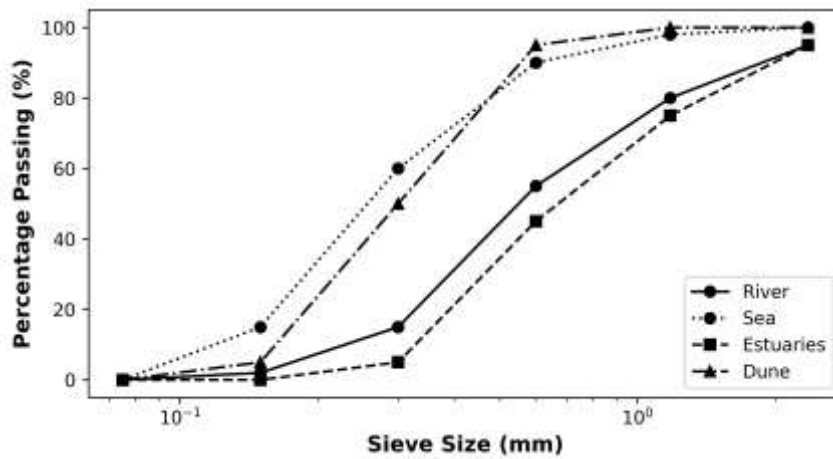


Fig 2. Particle size distribution curves for all four sand types showing the gradation differences.

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

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

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 significantly among sand types, directly impacting concrete durability (Table 3, Figure 3). River sand showed excellent compliance (179 mg/kg) at 64% below permissible limits. Dune sand also met requirements (215 mg/kg) with minimal corrosion risk. The bar chart clearly illustrates sea sand's excessive chloride content requiring treatment.

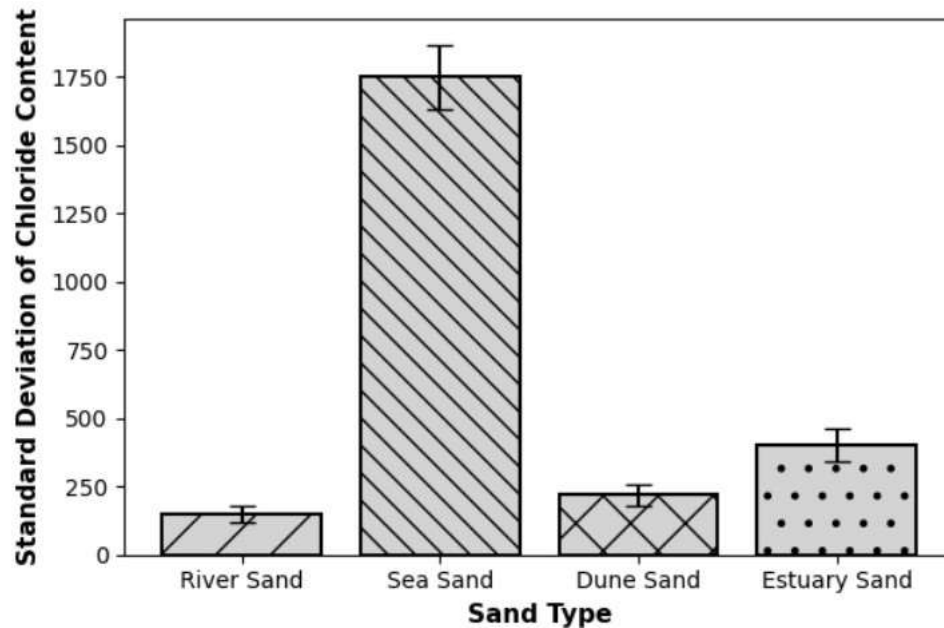


Fig 3. Chloride content comparison across sand types with BS 8500-1:2023 permissible limit (500 mg/kg)

Table 3: Chloride Content Analysis

Sand Type	Chloride Content (mg/kg)	BS 8500-1:2023 Limit	Compliance Status
River	179 ± 5.5	500	Excellent
Sea	1,796 ± 7.5	500	Exceeds by 259%
Dune	215 ± 5.5	500	Good
Estuary	431 ± 1.5	500	Borderline

Sea sand exceeded limits dramatically (1,796 mg/kg), requiring extensive desalination treatment. Estuary sand approached threshold levels (431 mg/kg), suggesting blending or washing protocols needed for safe use.

3.2 Concrete Performance

Concrete performance results are presented to assess the structural implications of incorporating different sand types in Grade 30 mixes. The evaluation emphasizes strength-related parameters, as they are critical indicators of load-bearing capacity and durability in structural applications. The analysis is structured to first examine compressive

strength development, followed by tensile performance, thereby providing a comprehensive understanding of mechanical behavior.

3.2.1 Strength Development

Compressive strength results revealed clear performance distinctions among sand types (Table 4, Figure 4(a)(b)). River sand achieved excellent 28-day strength (34.2 MPa), exceeding Grade 30 requirements with typical conical failure mode indicating sound structural integrity.

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

^aValues 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 demonstrated marginal compliance (31.8 MPa) despite fine particle size, with angular grains potentially improving packing density. The splitting failure mode reflected high internal tensile stresses, which may result from particle interlock, gradation effects, or workability differences during casting. The mode remained structurally acceptable for Grade 30 applications.

Sea sand underperformed significantly (27.5 MPa), consistent with chloride-induced microcracking and poor aggregate-cement bonding mechanisms reported in literature (Ramana, 2017; Zhao et al., 2019). While direct microstructural analysis was not conducted in this study, The observed shear failure patterns indicated brittle behavior, though failure modes reflect combined influences of chloride content, gradation, and workability rather than sand type alone. The concrete remains unsuitable for structural applications without treatment. Estuary sand fell short of Grade 30 requirements (29.3 MPa), which may be attributed to bimodal gradation creating void content and weak planes. The observed delamination failure pattern is consistent with inhomogeneous microstructure, though additional characterization would be needed to confirm this mechanism. The graph shows river sand achieving highest strength, followed by dune sand meeting Grade 30 requirements (30 MPa horizontal line), while sea and estuary sands fall short.

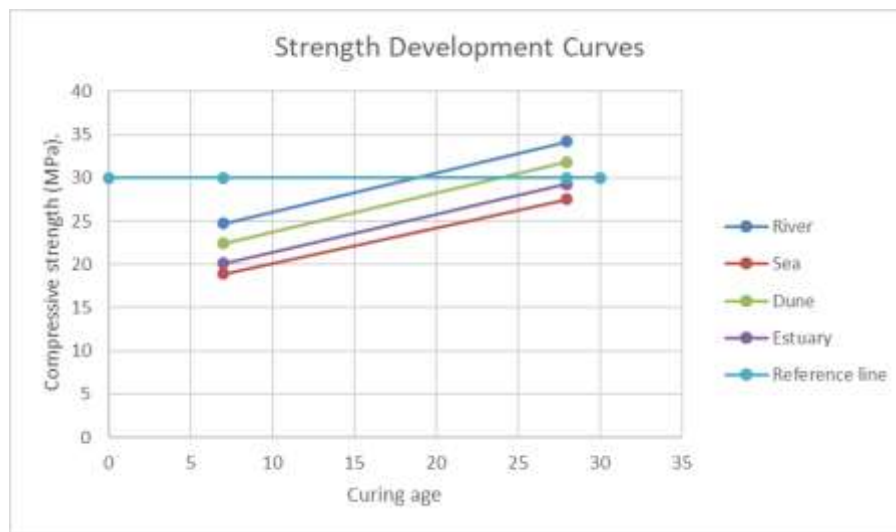


Fig 4(a). Compressive strength development over time (7 and 28 days) for concrete made with different sand types.

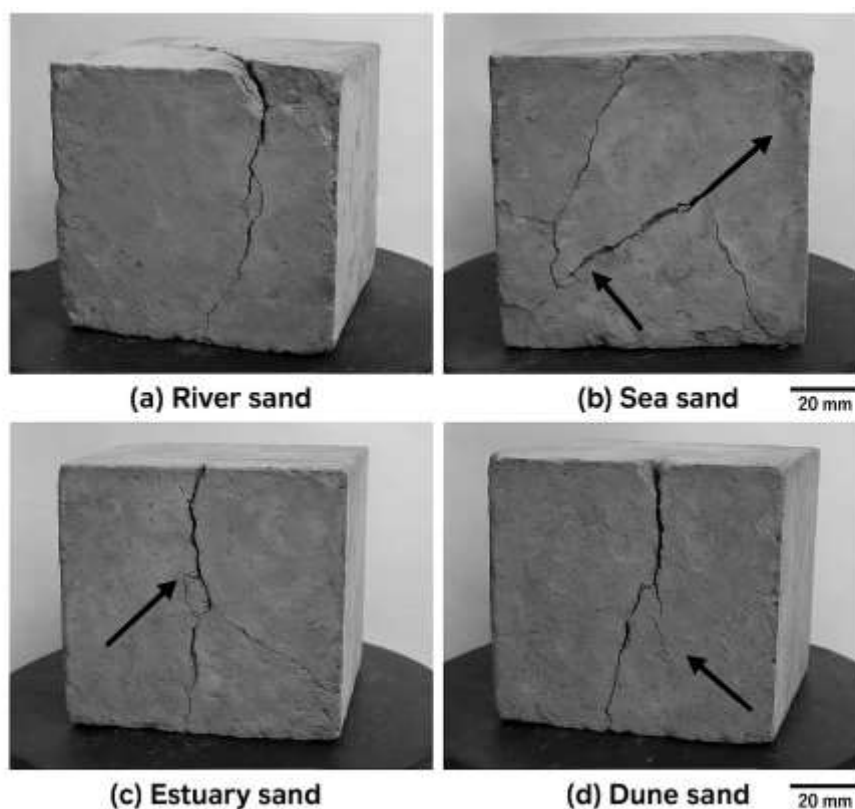


Fig. 4(b). Failure mode comparison of 150 mm concrete cubes at 28 days: (a) River sand showing conical failure with intact edges, (b) Sea sand exhibiting sudden shear plane with explosive spalling, (c) Dune sand displaying diagonal splitting at 45° angle.

The superior performance of river sand aligns with established literature on optimal gradation and particle morphology (Ferraris, 2001). The well-graded distribution (FM = 2.8) ensures efficient particle packing, reducing void content and enhancing cement-aggregate bonding. Dune sand's competitive strength despite finer particles can

be attributed to angular grain morphology from aeolian weathering processes, which increases mechanical interlock (Rashad, 2020). Sea sand underperformance is likely associated with chloride-induced mechanisms during cement hydration, as documented by Ramana (2017). Literature suggests excessive Cl^- ions interfere with C-S-H gel formation and promote expansive ettringite formation in the interfacial transition zone, though these mechanisms were not directly verified through microstructural analysis in the present study. The observed shear failure mode indicates reduced ductility a critical concern for seismic applications. Estuary sand's marginal performance reflects its complex mineralogy and bimodal gradation. The gap-graded distribution creates localized weak zones where inadequate fine material fails to fill voids between coarse particles. This phenomenon, termed "particle segregation," reduces homogeneity and creates preferential crack propagation paths (Brouwers and Radix, 2005).

3.2.1.1. 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 Figure 5. The tensile-to-compressive strength ratios ranged from 0.08 to 0.10, aligning with established empirical relationships for normal-weight concrete.

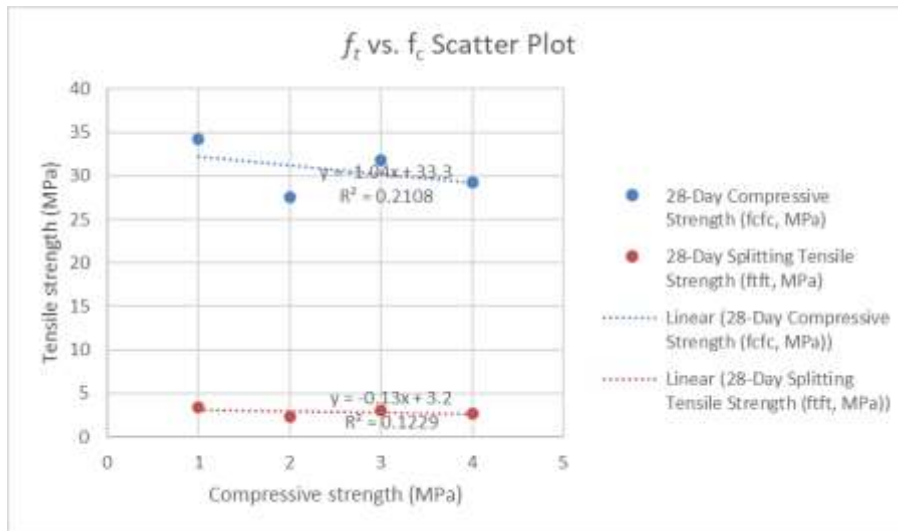


Fig 5. Correlation between compressive and tensile strengths for all sand types.

The scatter plot demonstrates the linear relationship with river and dune sands showing superior performance in both parameters.

3.3 Sustainability Assessment

Sustainability assessment integrates technical performance with environmental and economic considerations to establish viability of alternative sands for large-scale adoption. This evaluation extends beyond laboratory strength testing to encompass resource depletion impacts, processing energy requirements, and lifecycle costs. The following subsections examine environmental footprint, economic feasibility, and overall performance ranking.

3.3.1 Environmental Impact

Comparative assessment indicates that alternative sands require varying degrees of processing, with associated energy and resource inputs. Dune sand requires minimal processing beyond grading, while sea sand necessitates extensive 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) may provide economic advantages over continued river sand extraction. Sea sand processing requires higher capital investment for desalination infrastructure, offset by abundant coastal availability. Figure 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 assumed 50 km average distance to Colombo construction sites at LKR 15/ton-km. Environmental externalities

were estimated using carbon pricing equivalent (LKR 2,500/ton 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 10-year operational lifespan.

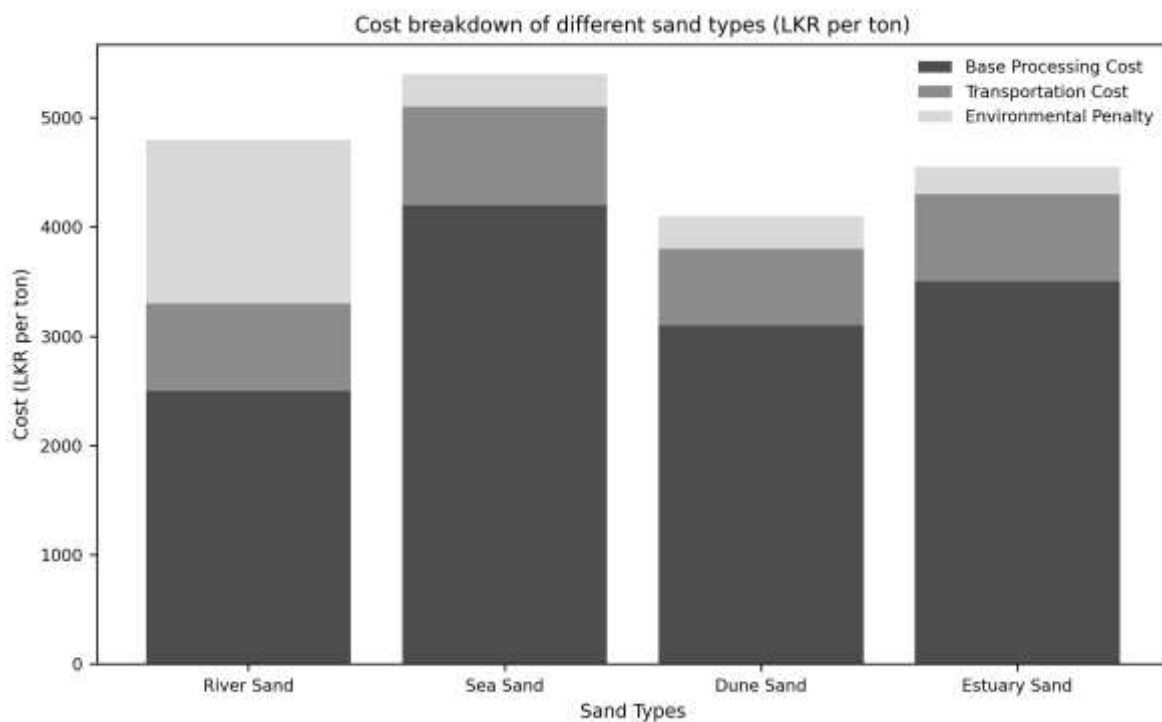


Fig 6. Comparative cost analysis showing estimated total cost per ton including processing, transportation, and modeled environmental externalities (based on carbon-equivalent ecosystem service valuation).

3.3 Performance Ranking

Based on combined technical, environmental, and economic criteria as illustrated in Figure 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 in 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), estuary sand must 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 any structural elements, including reinforced masonry or load-bearing walls, is not recommended based on 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.

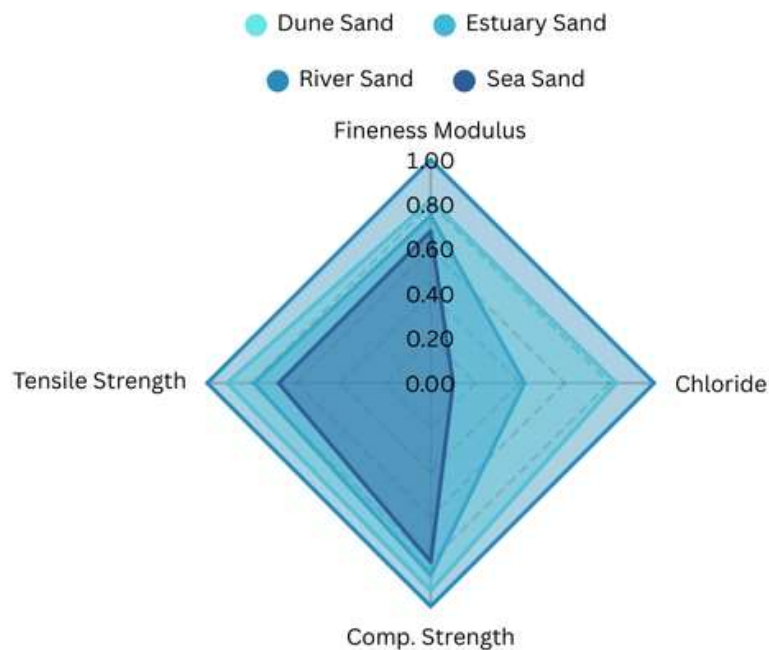


Fig 7. Multi-criteria performance radar chart comparing all sand types across five parameters: compressive strength, tensile strength, chloride compliance, gradation quality, and environmental sustainability. Dune sand shows the most balanced profile as a river sand alternative.

4.3. Study Limitations and Future Research

While this study provides valuable insights into Sri Lankan alternative sands, several limitations warrant acknowledgment:

1. **Durability Assessment:** Long-term durability parameters including chloride penetration resistance, sulfate attack resistance, and freeze-thaw performance were not evaluated. Future studies should conduct accelerated aging tests per ASTM C1202 and BS 1881-124 (ASTM, 2018).
2. **Microstructural Analysis:** The absence of SEM/EDS or XRD analysis limits understanding of interfacial transition zones and hydration product formation. Advanced microscopy would elucidate performance mechanisms (Shetty, 2019, Neville, 2011, Mindess, 2003).
3. **Blending Optimization:** Systematic investigation of blend proportions (e.g., 70% dune + 30% crushed sand) could optimize gradation and performance beyond single-source applications.
4. **Economic Data:** Cost analysis was based on market surveys rather than controlled lifecycle assessment. Comprehensive economic modeling including carbon footprint analysis is recommended.
5. **Sample Diversity:** Single-source sampling for each sand type may not capture regional variations. Multi-site sampling would strengthen generalizability. Future research should prioritize:
 - (a) 5-year durability monitoring of field structures,
 - (b) development of rapid chloride removal protocols,
 - (c) standardization of alternative sand specifications for Sri Lankan codes.
6. **Mix Design Variables:** This study maintained constant fine aggregate content (720 kg/m^3) across all sand types to reflect common field practices where aggregate substitution occurs on a volume basis. However, the different fineness moduli (1.9-2.8) and gradations among sand types represent a confounding variable that may have influenced workability and strength outcomes independently of intrinsic material properties. While this approach maintains practical relevance for industry application, 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 consistent slump (75-100 mm) may have masked differences in water demand related to particle shape and surface area.

5. CONCLUSIONS

This comprehensive evaluation demonstrates that Sri Lankan alternative sands can successfully replace river sand in concrete production when properly characterized and processed. Key findings suggest that Dune sand demonstrates technical viability for structural concrete, achieving 31.8 MPa compressive strength with a chloride content of 215 mg/kg, requiring minimal processing, while river sand, though superior at 34.2 MPa, faces sustainability challenges due to environmental concerns. Sea sand shows potential after desalination, which effectively reduces its initial chloride content of 1,796 mg/kg to acceptable levels, whereas estuary sand, with marginal performance, is best suited for non-structural applications. The adoption of alternative sands can significantly reduce pressure on river ecosystems while maintaining construction quality, with dune sand and processed estuary sand presenting the most balanced options in terms of performance, sustainability, and economic feasibility. Effective implementation requires coordinated efforts through regulatory enforcement, development of processing facilities, and industry training, with phased adoption in non-critical applications recommended to build confidence and technical expertise. Furthermore, future research should focus on evaluating long-term durability, optimizing blending ratios, and advancing cost-effective treatment technologies, thereby laying the foundation for sustainable construction material policies that support Sri Lanka's infrastructure growth while safeguarding natural ecosystems

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