



MECHANICAL STABILIZATION OF DUNE SAND USING REFRACTORY BRICK WASTE: EXPERIMENTAL EVALUATION OF COMPACTION, SHEAR STRENGTH AND CBR

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Abstract

Dune sand is widely available but its low cohesion, relatively uniform grading and limited bearing resistance can restrict its direct use in pavement and other geotechnical works. This study investigates mechanical stabilization of dune sand by partial replacement with refractory brick waste (RBW), treating an industrial/construction waste as a granular modifier. The experimental programme comprised particle-size characterization, Standard Proctor compaction, direct shear testing and California Bearing Ratio (CBR) testing for 0, 10, 20 and 30% RBW mixtures. The source thesis reports a dune sand specific gravity of 2.67, bulk density of 1.62 g/cm³ and water absorption of 1.25%; RBW has a specific gravity of 2.64 and water absorption of 0.2%. The tabulated results show that OMC increases from 16.5% for untreated sand to 17.2% at 20–30% RBW, while MDD decreases from 1.80 to 1.77 g/cm³. The reported direct-shear parameters increase from $c = 0$ and $\phi = 10.15^\circ$ for sand to $c = 0.131 \text{ kg/cm}^2$ and $\phi = 12.08^\circ$ at 20% RBW, before decreasing at 30%. CBR values are reported as 2.25, 3.456, 4.19 and 4.19% under soaked conditions for 0, 10, 20 and 30% RBW, respectively. Recent literature confirms that waste-derived granular and reactive materials can improve aeolian-sand grading, bearing capacity and sustainability. The combined evidence indicates that RBW is a promising mechanical stabilizer; however, the manuscript identifies an internal inconsistency in the original thesis between the tabulated shear parameters and the stated 10% optimum, which should be verified against the original laboratory sheets before journal submission.

Keywords: Dune sand; refractory brick waste; mechanical stabilization; direct shear; CBR; compaction; sustainable geotechnical engineering; construction waste.

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Introduction

Dune sand is one of the most widely available natural geomaterials in arid, semi-arid and alluvial regions, but its engineering application is often restricted because of its poor geotechnical characteristics. The predominance of rounded particles, narrow particle-size distribution, low fines content, weak interparticle interlocking and negligible apparent cohesion makes dune sand particularly vulnerable to deformation and erosion under external loading and environmental actions. These characteristics can result in inadequate bearing capacity, excessive deformation and poor resistance to penetration when dune sand is used directly in pavement subgrades, embankments, foundations and other geotechnical structures. Consequently, improvement of the engineering properties of dune sand is essential for its safe and sustainable utilization in civil engineering applications.

Conventional soil stabilization techniques generally involve the addition of cementitious or chemical materials such as cement, lime and bituminous products. Although these materials can significantly improve strength and stiffness, their extensive use is associated with high energy consumption, greenhouse-gas emissions, cost and environmental impacts. The increasing demand for sustainable construction practices has therefore encouraged researchers to investigate alternative stabilizing materials derived from industrial, agricultural and construction wastes. Waste-based stabilization provides a dual benefit by improving soil performance while simultaneously reducing the quantity of waste requiring disposal. Among different waste materials, ceramic and brick-derived wastes have received considerable attention because of their mineralogical composition, relatively high silica and

alumina contents, angular particle characteristics and availability in large quantities.

The generation of construction and demolition waste has increased substantially with rapid urbanization and infrastructure development. Fired clay bricks constitute a significant proportion of construction waste in many developing countries, including India. A considerable quantity of broken bricks, rejected bricks and demolition-derived brick fragments is disposed of in open areas or landfills. Improper disposal of refractory and brick waste can occupy valuable land and may create environmental and aesthetic problems. Recycling such waste as a soil-stabilizing material can therefore contribute to the principles of circular economy and sustainable geotechnical engineering. When crushed or processed into suitable particle sizes, refractory brick waste (RBW) can alter the particle-size distribution of poorly graded sand and improve particle interlocking. In addition, the presence of reactive silica- and alumina-bearing constituents may contribute to cementitious or pozzolanic reactions under appropriate conditions.

Previous studies have demonstrated the potential of brick and ceramic wastes for improving the engineering behavior of weak soils. Blayi et al. (2020), for example, investigated waste brick powder for stabilization of high-plasticity silt and reported improvements in compaction characteristics, unconfined compressive strength and California Bearing Ratio (CBR), accompanied by reductions in plasticity and swelling characteristics. Such findings indicate that brick-derived materials can provide both mechanical and physicochemical improvement of soil. However, the behavior of waste brick materials depends strongly on the type of soil,

particle size, percentage of waste, compaction conditions and testing environment. Therefore, results obtained for cohesive soils cannot be directly generalized to dune sand, where the dominant stabilization mechanism is likely to involve changes in gradation and particle interlocking rather than reduction of plasticity.

Recent research has increasingly focused specifically on the stabilization of aeolian and dune sands using waste and recycled materials. Arias-Trujillo et al. investigated the mechanical stabilization of aeolian sand using ceramic brick waste aggregates and reported improvement in particle-size distribution and bearing performance. Their investigation demonstrated that an appropriate proportion of ceramic brick waste could substantially improve the mechanical response of aeolian sand, with approximately 30% waste aggregate providing favorable performance. Amiri et al. (2023) examined the utilization of municipal solid-waste-derived materials, including fired clay brick powder, for stabilizing aeolian sand. Their results demonstrated that waste-based materials could develop substantial strength through cementitious and geopolymer-related reactions. Similarly, Smaida et al. (2023) investigated dune sand stabilization using crushed sand, silt and blast-furnace slag and reported substantial improvement in CBR and shear strength. These studies confirm the growing potential of waste-derived materials for improving problematic sandy soils.

Despite these developments, several research gaps remain. First, many previous investigations have concentrated on powder-form waste, chemically activated materials or combinations of several industrial by-products. Comparatively fewer studies have evaluated refractory brick waste as a relatively simple granular stabilizer

for dune sand using a systematic variation of waste content. Second, the simultaneous evaluation of compaction, shear strength and bearing characteristics is essential because improvement in one engineering property does not necessarily imply improvement in all performance parameters. Third, the optimum stabilizer content should be established using an integrated assessment rather than relying on a single parameter such as maximum dry density or CBR. Finally, the applicability of locally available waste brick materials for sustainable stabilization of dune sand requires further investigation under laboratory conditions representative of practical field applications.

The present study addresses these issues by experimentally investigating the stabilization of dune sand using refractory brick waste. Natural dune sand and refractory brick waste were first characterized in terms of their basic physical and engineering properties. Four mixtures were considered: untreated dune sand (M0), 10% RBW replacement (M10), 20% RBW replacement (M20) and 30% RBW replacement (M30). The experimental programme included particle-size analysis, specific gravity, water absorption, moisture content, Standard Proctor compaction, direct shear testing and CBR testing. The objective was to evaluate the influence of increasing RBW content on density, optimum moisture content, shear strength parameters and bearing capacity under soaked and unsoaked conditions.

The study is particularly relevant because the stabilization approach utilizes a waste material that can potentially be sourced locally and incorporated with minimum processing compared with conventional chemical stabilization. Modification of the gradation of dune sand through the introduction of relatively coarser and more angular brick particles can

increase mechanical interlocking and frictional resistance. Depending on the waste characteristics and degree of pulverization, additional physicochemical interactions may also contribute to strength development. Thus, RBW has potential not only as a waste-disposal solution but also as a sustainable geotechnical material.

The experimental results provide a basis for identifying the influence of RBW content on the engineering performance of dune sand and for determining a practically suitable stabilization range. Particular attention is given to the relationship between compaction behavior, shear strength and CBR, since these properties are directly relevant to earthworks, embankments and pavement subgrades. The study also compares the observed behavior with findings reported in recent literature to establish the contribution of the present investigation to sustainable soil stabilization research.

Overall, the research contributes to the development of waste-based ground improvement techniques by demonstrating the potential use of refractory brick waste for improving the engineering performance of dune sand. The approach supports resource conservation, reduction of construction waste and development of low-cost stabilization alternatives. The findings can provide a foundation for further investigations involving larger-scale laboratory studies, durability assessment, field trials and optimization of RBW particle size and content for practical geotechnical applications.

1.1 Research rationale

- Use a waste-derived aggregate to correct the weak grading of dune sand without relying on a conventional cementitious binder.
- Quantify the influence of RBW content on compaction, shear-strength parameters and pavement-related bearing resistance.

- Compare the present results with recent research on ceramic/brick waste and other waste-derived dune-sand stabilizers.
- Identify a defensible optimum range while explicitly checking consistency among the measured parameters.

1.2 Contribution of the present manuscript

The principal contribution is the conversion of the thesis-scale experimental dataset into a concise journal manuscript and its placement within the research landscape. In particular, the manuscript compares the present 0–30% RBW series with recent studies that investigated ceramic brick waste aggregates, waste brick powder and waste-derived binders for aeolian sand. The literature shows that the present topic is directly aligned with an active sustainability-oriented research direction.

Earlier work established that dune sand can be improved by adding granular ceramic waste, cement, lime-bentonite and other modifiers. The thesis cites Ameta and co-workers on ceramic tile waste, reporting increases in MDD, CBR and friction angle with increasing waste particle size/content. It also summarizes studies on sand–gravel mixtures and soil–rock mixtures, emphasizing the role of particle size, relative density and coarse-particle content.

Blayi et al. (2020) investigated waste brick powder in high-plasticity silt using 6–30% additions and evaluated Atterberg limits, compaction, swelling, UCS, CBR and permeability. Their results showed reductions in plasticity-related parameters and increases in MDD, UCS and CBR with WBP addition. Although the soil type differs from dune sand, the study demonstrates the broader feasibility of brick-derived waste as a geotechnical stabilizer.

Arias-Trujillo et al. investigated

mechanical stabilization of aeolian sand from Jeddah using ceramic brick waste aggregates at 15, 30 and 45%. The study specifically addressed the scarcity of coarse fraction in aeolian sand and evaluated grading, compaction and CBR under different confinement conditions, with SEM support. A 30% replacement was identified as optimal in that experimental system; confined CBR values at the two higher replacement levels were around 33%, approximately three times the untreated value.

Amiri, Toufigh and Toufigh (2023) evaluated fired clay brick powder together with eggshell and recycled glass powders as waste-derived precursors for aeolian-sand stabilization. Their alkali-activated

system produced C-S-H and N-A-S-H type gels and achieved a reported 91-day UCS of 5.32 MPa for the optimum composite. This work demonstrates a chemical/alkali-activated route, whereas the present study intentionally focuses on mechanical stabilization by RBW particles.

Smaida et al. (2023) studied dune-sand stabilization using crushed sand, silt and lime-activated blast-furnace slag. The programme included grain-size distribution, Proctor compaction, CBR, compressive strength, shear strength and compressibility. The authors reported substantial improvement in CBR and cohesion, demonstrating the value of combined grading correction and hydraulic binding for pavement applications.

Comparative literature matrix

Study	Soil / waste	Main variables	Key finding relevant to present work
Ameta et al. (thesis-cited)	Dune sand / ceramic tile waste	Particle size; 5–30%	MDD and CBR increased; ϕ increased with particle size/content.
Blayi et al. (2020)	High-plasticity silt / waste brick powder	6–30% WBP	MDD, UCS and CBR increased; plasticity and swelling decreased.
Arias-Trujillo et al. (2023)	Jeddah aeolian sand / ceramic brick aggregate	15, 30, 45%	Improved grading and confined CBR; 30% identified as optimum.
Amiri et al. (2023)	Aeolian sand / fired clay brick + ESP + RGP	Waste precursors + NaOH/KOH	Alkali activation produced high long-term UCS.
Smaida et al. (2023)	Dune sand / crushed sand, silt, activated slag	Grading correction + binder	CBR, cohesion and compressive strength improved.
Present study	Dune sand / RBW	0, 10, 20, 30%	Compaction, direct shear and CBR response evaluated.

2. Identified research gap

The recent literature indicates that

ceramic/brick waste is increasingly investigated, but direct comparison among studies remains difficult because waste form, particle size, replacement basis, confinement, curing and test conditions differ. A particularly useful gap is the systematic characterization of low-percentage RBW as a purely mechanical granular stabilizer using direct shear together with compaction and CBR on the same dune-sand material.

- Need to distinguish mechanical grading correction from chemical stabilization.
- Need to report particle size and replacement basis clearly because these strongly control packing and friction.
- Need to examine whether the optimum inferred from shear strength agrees with the optimum inferred from CBR and compaction.

- Need to validate laboratory optimum against field confinement, durability, wetting and repeated loading.
- Need to report environmental and economic implications before recommending large-scale use.

3. Materials and Experimental Programme

3.1 Dune sand

The source thesis reports the dune sand as a granular material characterized by sieve analysis in accordance with IS 2386 (Part 1)-1963. The reported particle-size data show 93.1% passing 2 mm, 88.0% passing 1 mm, 85.2% passing 0.6 mm, 83.4% passing 0.425 mm, 81.0% passing 0.30 mm, 17.3% passing 0.15 mm and 4.8% passing 0.075 mm. The thesis reports $C_u = 1.785$ and $C_c = 0.926$, indicating a relatively poorly graded sand.

Property	Dune sand	RBW
Moisture content	0.20%	0.10%
Specific gravity	2.67	2.64
Bulk density	1.62 g/cm ³	—
Water absorption	1.25%	0.20%
Reported C_u	1.785	—
Reported C_c	0.926	—

3.2 Refractory brick waste

RBW was used as a granular replacement material. The thesis prepared mixtures by replacing sand by weight at 10, 20 and 30%, with

untreated sand as the control. The reported RBW specific gravity is slightly lower than that of sand, while its water absorption is substantially lower.

3.3 Mix designation

Mix	Sand (%)	RBW (%)
M0	100	0
M10	90	10
M20	80	20
M30	70	30

4. Test Methods

4.1 Particle-size analysis

Approximately 500 g of soil was subjected to dry sieve analysis using a sequence including 4.75, 2.0, 1.0,

0.60, 0.425, 0.30, 0.15 and 0.075 mm sieves. Percentage retained, cumulative percentage retained and percentage finer were determined. The particle-size curve was used to obtain D₁₀, D₃₀ and D₆₀ and hence

Cu and Cc.

cohesion, c , and friction angle, ϕ .

4.2 Standard Proctor compaction

The reported compaction setup used a 997.46 cm³ mould, 2.6 kg rammer, 31 cm free fall, three layers and 25 blows per layer. The soil mass used was approximately 3 kg passing 4.75 mm. Moisture-density relationships were obtained for each mixture and the OMC and MDD were identified from the corresponding curves.

4.3 Direct shear test

Direct shear testing was conducted using a 6 cm × 6 cm shear box. Normal stresses of 0.5, 1.0 and 1.5 kg/cm² were applied. The thesis records a strain-controlled shear rate around 0.25 mm/min in the detailed test tables (one general description states 0.2 mm/min). This discrepancy should be standardized in the final journal Methods section using the laboratory logbook. The failure envelope was used to estimate

4.4 California Bearing Ratio

CBR tests were performed for untreated and RBW-treated sand in soaked and unsoaked conditions at the reported compaction condition. The thesis used 56 blows and a penetration rate of 1.25 mm/min for the reported CBR observations.

4.5 Data treatment

The present manuscript uses the reported values as supplied in the thesis. No unsupported laboratory values have been generated. Summary statistics are used only to compare the reported mixtures. Where the thesis contains internal inconsistencies, they are identified rather than silently corrected.

5. Results and Discussion

5.1 Compaction Behavior

The reported optimum moisture content and maximum dry density are summarized below.

RBW (%)	OMC (%)	MDD (g/cm ³)	Change in MDD vs. M0
0	16.5	1.80	—
10	16.9	1.78	−1.11%
20	17.2	1.77	−1.67%
30	17.2	1.77	−1.67%

The data indicate a small increase in OMC with RBW addition and a modest reduction in MDD. This trend is consistent with the lower specific gravity of RBW (2.64) relative to the sand (2.67) and with changes in packing arrangement. The original thesis conclusion stating that MDD increases with increasing RBW is not consistent with its own summarized OMC–MDD table, which reports MDD falling from 1.80 to 1.77 g/cm³. The journal version should therefore use the numerical table and verify the original calculations before submission.

5.1.1 Detailed interpretation of compaction

At 10% RBW, the reported OMC

increases from 16.5 to 16.9% while MDD decreases from 1.80 to 1.78 g/cm³. At 20% RBW, OMC reaches 17.2% and MDD reaches 1.77 g/cm³. Increasing RBW to 30% does not change the reported OMC or MDD further. Thus, within the investigated range, the effect is more evident as a gradual moisture-demand increase and a small density reduction rather than a large change in compactability.

Engineering interpretation

- The addition of RBW changes the particle-size distribution and packing structure.
- The lower RBW specific gravity contributes to a lower mass density at comparable compacted volumes.
- The plateau between 20 and 30%

suggests limited additional compaction benefit beyond 20%.

- The optimum for compaction alone cannot be selected solely from MDD because the highest MDD occurs in untreated sand.
- Therefore, shear strength and CBR must be considered jointly for stabilization optimization.

typographical and transcription errors in tables and graph labels. For Scopus submission, all reported OMC/MDD values should be checked against the original Proctor sheets, recalculated using the standard dry-density equation, and rounded consistently (preferably to 0.01 g/cm³ and 0.1% moisture content).

Quality-control note

The original thesis contains several

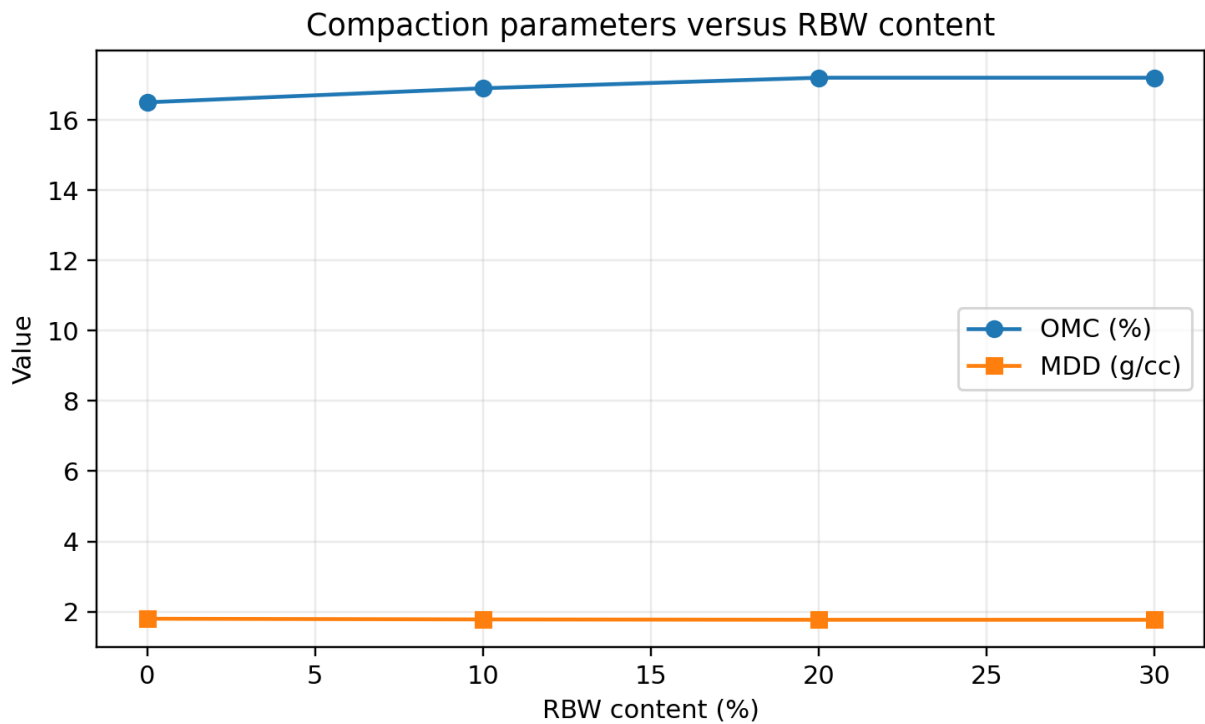


Figure 1. Reported compaction parameters of dune sand–RBW mixtures.

5.2 Direct Shear Strength

The manuscript reports the following

Mohr–Coulomb parameters from the normal stress–shear stress envelopes.

RBW (%)	c (kg/cm ²)	φ (degree)	c (kPa, approx.)
0	0.000	10.15	0.0
10	0.125	11.05	12.26
20	0.131	12.08	12.85
30	0.075	9.42	7.36

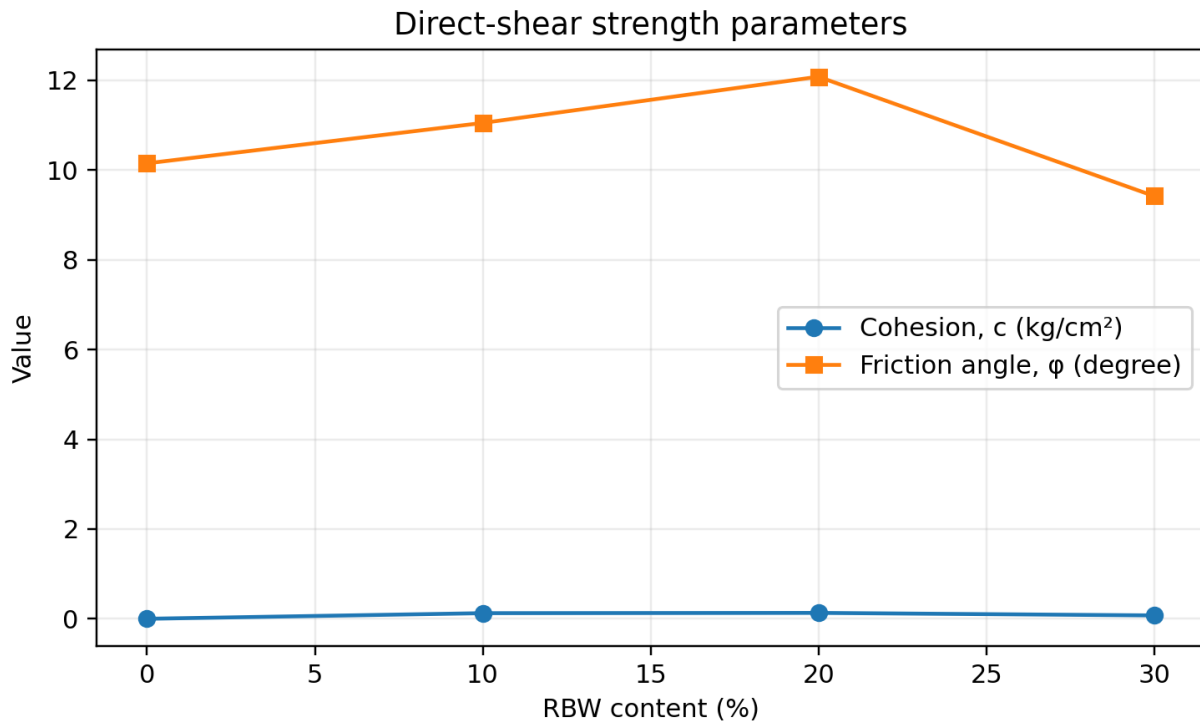


Figure 2. Reported direct-shear strength parameters versus RBW content.

The tabulated values show a non-monotonic response. Both c and ϕ increase from 0 to 20% RBW, followed by a decline at 30%. The maximum reported friction angle is 12.08° at 20% RBW, while the maximum cohesion is 0.131 kg/cm² at 20% RBW.

5.2.1 Shear-strength mechanism and optimum-dose issue

The initial increase in shear resistance can reasonably be associated with improved particle interlocking and the introduction of angular/coarser RBW particles into the dune-sand matrix. At 30% RBW, the decline in both c and ϕ suggests that excessive replacement may disturb the efficient sand–waste packing arrangement, increase particle-to-particle incompatibility, or produce a less favorable contact network.

Important consistency check

The original thesis states that shear strength increases up to 10% RBW and then decreases and recommends 10% as the optimum dose. However, its own summary table reports $\phi = 12.08^\circ$ and $c = 0.131$ kg/cm² at 20% RBW, both higher than the

corresponding 10% values. The thesis also states that the friction angle at the selected condition is 32% higher than untreated sand. The increase from 10.15° to 12.08° is approximately 19.0%, not 32%.

Accordingly, the present manuscript does not claim that 10% is definitively optimal. Instead, the defensible conclusion from the reported summary table is that 20% produces the highest listed c and ϕ , while the original narrative recommends 10%. This must be resolved from the original shear-test observations and regression equations before submission.

Recommended verification

- Recalculate the failure envelopes from the three peak shear stresses at each normal stress.
- Use identical failure criteria for all mixtures.
- Report R^2 of each linear fit and uncertainty/replicate variability.
- Confirm whether the tabulated c and ϕ were derived from peak or residual shear stresses.
- Then define the optimum using a multi-response criterion including

shear strength and CBR.

5.3 California Bearing Ratio

RBW (%)	Soaked CBR (%)	Unsoaked CBR (%)	Soaked change vs. M0
0	2.25	2.73	—
10	3.456	2.18	+53.6%
20	4.19	2.97	+86.2%
30	4.19	2.89	+86.2%

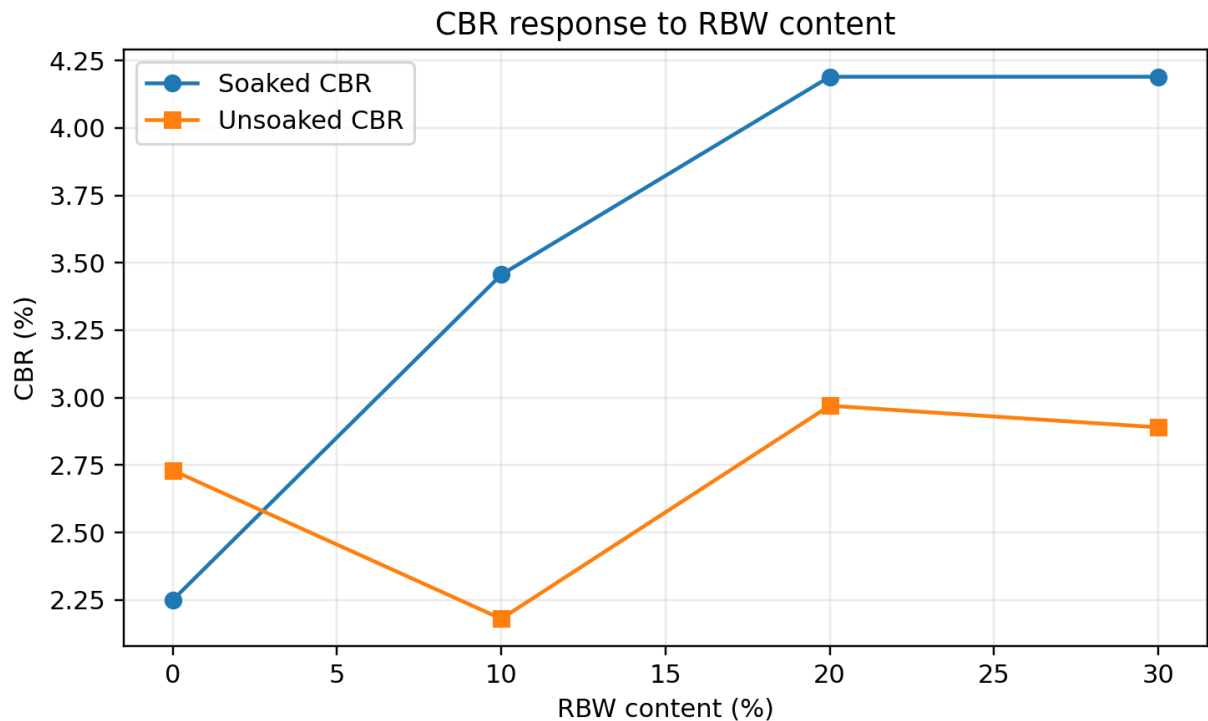


Figure 3. Reported soaked and unsoaked CBR values.

The soaked CBR rises from 2.25% for untreated sand to 3.456% at 10% RBW and 4.19% at 20 and 30% RBW. The unsoaked values fluctuate: 2.73% for untreated sand, 2.18% at 10%, 2.97% at 20% and 2.89% at 30%. Therefore, the evidence for improvement is strongest for the soaked series, whereas the unsoaked series does not show a monotonic trend.

5.3.1 CBR discussion

The increase in soaked CBR with RBW addition suggests that the granular waste contributes to a stronger load-transfer network under penetration. The improvement may result from better particle interlocking and a modified

gradation that reduces the weakness associated with a highly uniform sand.

The 20 and 30% mixtures have identical reported soaked CBR (4.19%), indicating that additional RBW beyond 20% did not improve the reported bearing index. From a combined performance perspective, this favours a lower replacement within the 20–30% range if the shear results are also confirmed.

Comparison with recent literature

Arias-Trujillo et al. reported a substantially larger confined CBR response for Jeddah aeolian sand treated with 15–45% ceramic brick

waste, with about 33% CBR for the two higher replacement levels under confined conditions. The much lower CBR values in the present dataset may reflect differences in sand grading, waste particle size, compaction, confinement and test configuration; therefore, absolute CBR values should not be compared without normalizing test conditions.

Blayi et al. found CBR increasing from 3.20% for untreated high-plasticity silt to 17.30% at 30% WBP. Again, the soil and waste form

differ from the present study, but the direction of response supports the potential of brick-derived materials for improving bearing resistance.

Practical implication

For pavement subgrade applications, the reported CBR improvement is encouraging but insufficient by itself for field recommendation. Subgrade classification, drainage, soaked design condition, traffic category and applicable pavement-design standards must be considered.

5.4 Integrated Performance Assessment

Criterion	0%	10%	20%	30%	Best reported level
OMC (%)	16.5	16.9	17.2	17.2	0% (lowest moisture demand)
MDD (g/cm ³)	1.80	1.78	1.77	1.77	0% (highest density)
c (kg/cm ²)	0	0.125	0.131	0.075	20%
φ (°)	10.15	11.05	12.08	9.42	20%
Soaked CBR (%)	2.25	3.456	4.19	4.19	20–30%
Unsoaked CBR (%)	2.73	2.18	2.97	2.89	20%

A multi-criteria reading of the reported dataset points toward 20% RBW as the strongest candidate for further validation: it provides the highest listed shear parameters, the highest soaked CBR jointly with 30%, and the highest unsoaked CBR. The original thesis recommendation of 10% is therefore best treated as a preliminary conclusion requiring recalculation.

5.5 Proposed stabilization mechanism

- Granular correction: RBW introduces particle sizes and shapes that modify the original dune-sand gradation.
- Void filling and packing: finer RBW fractions may occupy voids between sand grains.

- Interlocking: angular waste particles can increase mechanical interlock and frictional resistance.
- Contact-network modification: increasing replacement initially improves load transfer, but excessive replacement may disrupt the optimal sand–RBW skeleton.
- Environmental benefit: diversion of brick/refractory waste from disposal reduces the demand for virgin granular resources.

5.6 Sustainability and Engineering Significance

Waste-derived stabilization can provide two simultaneous benefits: improvement of weak soil and beneficial reuse of an otherwise

discarded material. Recent literature increasingly frames ceramic and brick waste as an alternative to conventional stabilizers, especially where the objective is to reduce cement consumption or recover construction and demolition waste.

The present study is particularly relevant to mechanical stabilization because it does not require an alkaline activator or curing period. This can simplify field application compared with geopolymer-based stabilization. However, the absence of a chemical binder also means that performance depends strongly on particle size distribution, density, confinement and moisture.

Potential applications

- Low-volume road and access-road subgrades, subject to required CBR criteria.
- Embankment fill or selected fill where grading and durability requirements are satisfied.
- Working platforms and temporary construction roads.
- Blended granular layers where locally available dune sand is otherwise unsuitable.
- Potential use in arid regions where ceramic/refractory waste is locally available.

Limitations

- Only four replacement levels are represented.
- No replicate variability or statistical significance is reported.
- Durability under repeated wetting–drying and cyclic loading is not established.
- Particle-size distribution of RBW is not fully reported in the manuscript dataset.
- Chemical/mineralogical characterization (XRD/XRF/SEM) is absent.
- Field-scale confinement and construction variability are not evaluated.

5.7 Comparison with the State of the Art

The recent literature can be divided into three broad approaches. First, mechanical stabilization uses waste aggregates to correct grading and increase interlocking; the Construction and Building Materials study by Arias-Trujillo et al. is the closest recent analogue to the present research. Second, powder-based stabilization uses brick fines as a modifier or reactive precursor, as in Blayi et al. (2020). Third, chemically activated systems combine waste precursors with alkaline activators or hydraulic binders, as in Amiri et al. (2023) and Smaida et al. (2023).

Approach	Typical material	Primary mechanism	Present study position
Mechanical	Brick/ceramic aggregate	Packing + interlocking	Directly applicable
Powder modifier	Waste brick powder	Fines filling + friction/chemical effects	Related but different particle form
Alkali activated	Brick/glass/eggshell powders	Geopolymer/C-S-H formation	Not used here
Hydraulic/binder	Slag + lime + grading correctors	Binding + grading correction	Not used here

This distinction is important for publication because the manuscript should not attribute cementitious or geopolymeric mechanisms to the present RBW treatment unless supported by chemical characterization. The safest interpretation is mechanical stabilization through particle-size and contact-network modification.

5.8 Statistical and Data-Quality Recommendations for Journal Submission

The thesis dataset is valuable, but the journal version should improve reproducibility and statistical defensibility.

- Test at least three replicate specimens for each mixture and report mean $\pm$ standard deviation.
- Provide the complete particle-size distribution of both sand and RBW, not only the sand.
- Report RBW particle-size range, shape description and processing method.
- State whether percentages are replacement by dry mass of sand or total dry mixture.
- Report exact compaction effort and the same terminology throughout the manuscript.
- State whether direct-shear strength is peak or residual strength.
- Report regression equations and R^2 for each Mohr–Coulomb envelope.
- Provide CBR load–penetration curves, not only final CBR values.
- Use consistent units: preferably kPa for stress and degrees for ϕ .
- Verify all arithmetic in the original tables before publication.

5.9 Discussion

The experimental evidence indicates that RBW changes the engineering response of dune sand in a dose-dependent manner. The untreated sand exhibits negligible apparent cohesion and a low friction angle, consistent with a cohesionless, relatively uniform granular material. Addition of RBW initially increases the apparent cohesion and friction angle, suggesting improved particle

interaction. The response reaches its reported maximum at 20% RBW and then declines at 30%, indicating that the stabilization effect is not indefinitely proportional to waste content.

Compaction shows a different response. OMC increases modestly while MDD decreases slightly. This means that the strength improvement cannot be attributed simply to a higher dry density. Instead, changes in particle interlock, gradation and the nature of contacts between sand and RBW appear to be important. This is an important observation for the manuscript because it supports a mechanical stabilization interpretation rather than a purely densification-based explanation.

The soaked CBR increase is also important because moisture commonly controls pavement-subgrade performance. The increase from 2.25% to 4.19% represents an approximately 86% relative increase. Nevertheless, the absolute value remains low for many pavement applications, so the stabilized material should not be claimed as a suitable base or subbase without additional testing and pavement-design verification.

The recent literature strengthens the relevance of the present study. Arias-Trujillo et al. demonstrated that ceramic brick aggregates can correct the deficient coarse fraction of aeolian sand and improve confined CBR. Amiri et al. demonstrated a different route using waste-derived alkali activation, while Smaida et al. combined grading correction with activated slag. These studies collectively support the concept that waste-derived materials can transform weak aeolian sands into more useful engineering materials, but they also demonstrate that the mechanism and optimum dosage are highly system-

specific.

The following compact table can be used in the Results section after raw-data verification.

Mixture	OMC (%)	MDD (g/cm ³)	c (kg/cm ²)	φ (°)	Soaked CBR (%)	Unsoaked CBR (%)
M0	16.5	1.80	0.000	10.15	2.25	2.73
M10	16.9	1.78	0.125	11.05	3.456	2.18
M20	17.2	1.77	0.131	12.08	4.19	2.97
M30	17.2	1.77	0.075	9.42	4.19	2.89

These values are transcribed from the submitted thesis. They should be treated as reported values pending verification against original laboratory observation sheets. The table should not be presented as statistically replicated data unless replicate results are available.

6. Conclusions

- The investigated dune sand is a weak, relatively poorly graded granular material with reported $C_u = 1.785$ and $C_c = 0.926$.
- RBW has a specific gravity of 2.64 compared with 2.67 for the dune sand and was incorporated at 10, 20 and 30% replacement levels.
- Reported OMC increases from 16.5% to 17.2%, while MDD decreases from 1.80 to 1.77 g/cm³ as RBW increases from 0 to 20–30%.
- The tabulated direct-shear parameters increase from $c = 0$, $\phi = 10.15^\circ$ for untreated sand to $c = 0.131$ kg/cm², $\phi = 12.08^\circ$ at 20% RBW, followed by a reduction at 30%.
- Reported soaked CBR increases from 2.25% for untreated sand to 4.19% at 20 and 30% RBW.
- Within the reported dataset, 20% RBW is the strongest candidate for further validation because it provides the highest listed cohesion and friction angle and the maximum soaked and unsoaked CBR values.
- The original manuscript recommendation of 10% RBW is inconsistent with its tabulated c – ϕ values and should be verified against the raw direct-shear data before journal submission.
- RBW provides a potentially

sustainable route for mechanical stabilization and waste valorization, but field suitability requires durability, repeated-load, environmental and economic validation.

On the basis of above work future recommendations are listed below:

- Investigate intermediate contents such as 15, 20, 25 and 30% RBW.
- Characterize RBW by XRD/XRF and SEM–EDS.
- Evaluate wetting–drying, freeze–thaw where relevant, abrasion and cyclic CBR performance.
- Study the effect of RBW particle size and particle shape separately.
- Conduct large-scale shear tests and field trial sections to capture confinement effects.
- Develop a multi-objective optimization using CBR, ϕ , c , MDD, OMC and cost/environmental indicators.

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