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Research Article

Co-valorization of local materials tuff and red brick waste mixture for use in road construction

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Abstract

This study investigates the co-valorization of red brick waste (RBW) as a partial replacement for tuff in desert road construction. Tuff, widely used in Algeria's Saharan roads, is a non-renewable volcanic material whose exploitation raises serious environmental concerns. The incorporation of RBW provides a sustainable alternative by reducing reliance on natural tuff reserves while simultaneously diverting construction waste from landfills, contributing to resource preservation and pollution reduction. To assess this approach, experimental mixtures were prepared with 0%, 10%, 20%, and 30% RBW, and their physical and mechanical behavior was evaluated through a comprehensive laboratory testing program. The methodology included Modified Proctor compaction tests to determine optimal moisture and density conditions, California Bearing Ratio (CBR) tests to assess load-bearing capacity, and Unconfined Compressive Strength (UCS) tests to evaluate strength development, all conducted under controlled conditions. Results revealed that the mixture containing 20% RBW exhibited the most favorable performance, achieving a UCS of 5.05 MPa and a CBR value of 83.53%, representing a significant improvement compared to tuff alone. The 30% RBW mixture also satisfied technical standards with a UCS of 2.8 MPa and a CBR value of 80.19%. These findings demonstrate that integrating RBW with tuff offers a practical and environmentally sustainable solution for road construction in desert regions.

1. Introduction

In recent decades, the depletion of natural resources and the accumulation of construction and demolition (C&D) wastes have become global concerns for sustainable infrastructure development. Road construction in particular consumes vast quantities of quarried aggregates and natural soils; however, their extraction and processing require high energy, generate substantial greenhouse gas emissions, and cause severe environmental impacts [1–4]. Consequently, the utilization of alternative local and recycled materials has emerged as a central theme in geotechnical and pavement engineering, aiming to address both engineering performance and environmental sustainability [5–8].

Construction and demolition waste, mainly consisting of concrete debris, bricks, asphalt fragments, and excavation residues, constitutes one of the largest waste streams worldwide [9-12].

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Traditionally, such waste has been landfilled, leading to environmental degradation and the loss of potentially reusable resources. Several studies have shown that recycling C&D waste in cementitious systems contributes positively to strength and durability. For example, Derabla and Moufida [13] demonstrated that red brick waste improved compressive strength in high-performance concrete, while Schackow et al. [14] reported that crushed brick aggregates enhanced long-term durability in mortars. Similarly, Saif et al. [15] observed that fired clay waste reduced shrinkage and improved density in cement-based composites. These results highlight the potential of C&D waste as a valuable raw material for sustainable construction. Recent reviews also emphasized its role in geotechnical engineering applications, where recycled aggregates improved compaction and increased CBR values [16,17].

Among the various C&D fractions, fired clay brick waste is particularly abundant in regions where masonry construction is common. Crushed brick particles exhibit mineralogical similarities to natural aggregates and have been used successfully as partial replacements in concrete, asphalt, and soil mixtures [18-21]. Studies have consistently shown improvements in load-bearing capacity, reduced swelling in clayey soils, and increased UCS values [22,23]. For instance, field-scale investigations showed that integrating brick powder into road base layers resulted in higher stability and durability under cyclic loading [24].

In parallel, indigenous geomaterials such as dune sands, lateritic soils, and especially tuff have long been utilized as cost-effective resources in arid and semi-arid regions. In Algeria, where nearly three-quarters of the land area is desert, tuff deposits cover approximately 300,000 km^2 and have facilitated the construction of thousands of kilometers of economical desert roads since the 1950s [25-27]. This led to the establishment of the Saharan Road Technology (TRS), a specific body of standards and practices adapted to local soils [28,29]. Tuff is valued for its cohesiveness upon compaction and drying, sometimes referred to as “self-stabilization” [30]. However, untreated tuff suffers from low resistance to water, resulting in reduced strength and durability. Several studies attempted to overcome these drawbacks: Goual et al. [31] reported that blending tuff with dune sand improved compaction and CBR values, while Akacem [32] showed that limestone fines increased UCS and shear resistance. Likewise, Moulay Omar et al. [33] demonstrated that sandy industrial residues yielded acceptable UCS and CBR results suitable for subbase layers. More recent findings also suggest that the addition of pozzolanic binders and crushed brick waste can significantly improve durability of tuff-based mixtures [34,35]. In addition, experimental works confirmed that combining tuff with dune sand or stabilizers enhanced compaction indices and bearing capacity under desert conditions [36,37].

Despite these efforts, the direct co-valorization of tuff with red brick waste (RBW) in pavement layers remains scarcely studied. RBW presents distinct mineralogical and granulometric characteristics that may contribute to improved packing, density, and strength. The novelty of this study lies in addressing two simultaneous challenges: the depletion of non-renewable tuff reserves and the environmental burden of RBW disposal. This dual valorization approach is particularly relevant for Algeria, where both materials are abundant, and sustainable road technologies are urgently needed. Accordingly, the present study evaluates the physical and mechanical properties of tuff–RBW mixtures through a laboratory program including Modified Proctor compaction, California Bearing Ratio (CBR), and Unconfined Compressive Strength (UCS) tests under controlled conditions. The key objective is to identify optimal substitution levels that enhance geotechnical performance while reducing reliance on virgin tuff. The findings provide scientific evidence supporting the integration of RBW with tuff as a practical, environmentally sustainable solution for road construction in desert regions.

2. Materials and Methods

2.1 Materials

The use of local materials in infrastructure development not only saves resources and reduces costs but also significantly preserves the environment. This study focuses on the use of tuff and red brick waste in road construction, where we used resources from the southernmost part of Algeria, specifically from wilaya d’Adrar, located about 1,500 kilometers southwest of the capital.

2.1.1 Local Materials

The studied tuff (Fig. 1.a) was extracted from a quarry located 11 km from Ahmed Draia University towards Oued Zin on the right in ADRAR Wilaya (Fig. 2). Similarly, the red brick waste (Fig. 1.b) was sourced approximately 3.1 km from the same university, near a red brick manufacturing facility known as Sarl Timadnine Briqueterie (Fig. 2).

(a)

(b)

Fig. 1. Used materials (a)Tuff oued zin; (b) Sarl red brick waste

Fig. 2. Study Area and Sampling Location in Adrar, Algeria

2.1.2 Geotechnical Characterization

According to Table 1, a chemical examination of the tuff showed that calcium carbonate ($CaCO_3$) predominated and made up more over 50% of the material. The characteristics of tuff benefit from this high calcium carbonate content.

Through the results of XRD analysis (Fig. 3a), it is shown that the tuff contains a large percentage of calcium carbonate ($CaCO_3$). This is consistent with the results of Table 1. As for the red brick waste, it contains a large percentage of biotite and some quartz, (Fig. 3b).

Table 1. Summary of chemical analysis results

Echantillons	Calcium Carbonate % ($CaCO_3$)	Sulfate (mg/kg)	Chloride (%)	Insoluble (%)
Tuff Oued Zin	53,7	27634	0,43	43,11

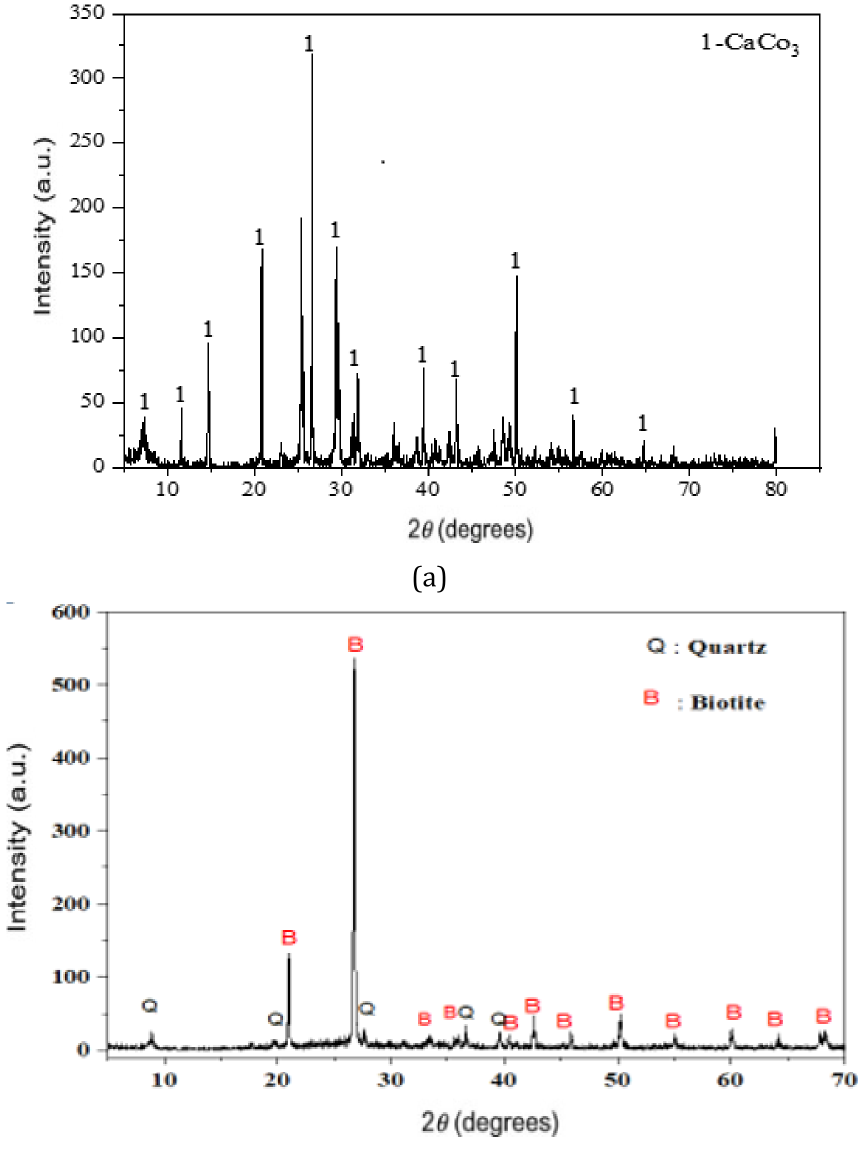

Fig. 3. X-Ray Diffraction patterns: (a) tuff Oued Zin (b) red brick waste

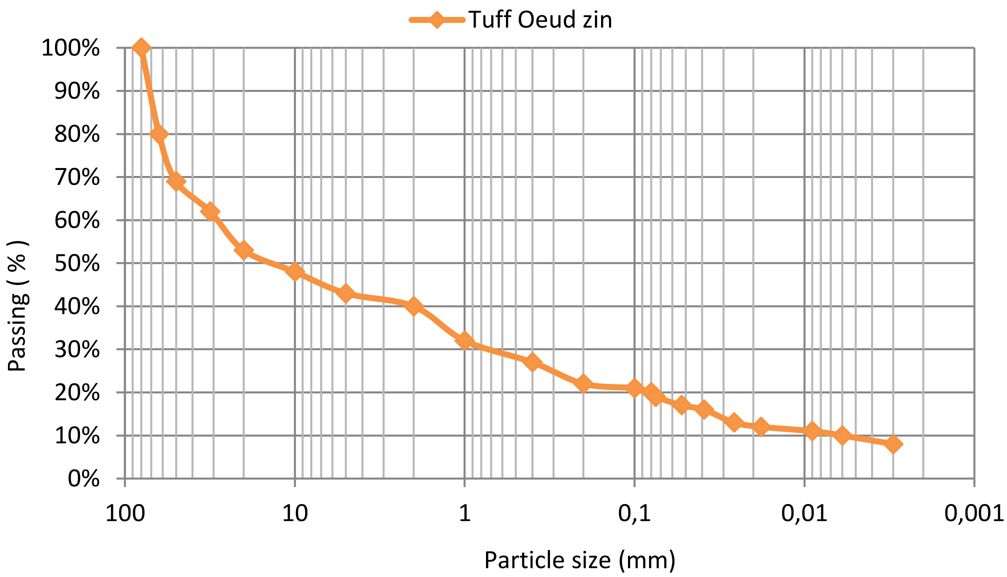

Fig. 4. Grain size distribution curves for tuff

Particle size analysis, conducted according to NF P 94-056[38], standards, assesses the size distribution and weight percentages of different grain families within a sample. The analysis of the tuff, illustrated in Figure 4, shows that the material comprises approximately 43% sand fraction (<2 mm) and 21% fines fraction (<0.80 mm). The granularity data reveal a wide spread in uniformity (Cu) and grain size, with the curvature coefficients (Cc) indicating a well-graded material. According to the test outcomes presented in Table 2, and following classifications from GTR [39], NF P 94 11- 300 [40], and the Unified Soil Classification System (USCS) [41], the Tuff is classified by the GTR guide as a soil containing both fine and coarse elements (C1A2ts). In the USCS framework, it is categorized as Silty gravel (GM).

Table 2. Geotechnical parameters of tuff

Parameter	Tuff	Unit
Physical		
Grains < 80 µm	21	%
Grains < 2 mm	43	%
Liquid limit (LL)	35,1	%
Plastic limit (PL)	25,7	%
Plasticity index (PI)	9,4	%
Apparent density (γ_{apa})	17,1	KN/m³
Absolute density (γ_{abs})	25,15	KN/m³
Sand equivalent	12,62	
Mechanical		
Maximum dry density γ_d Modified	19,1	KN/m³
Optimum water content W_{OPN} Modified	9,96	%
California burning ratio index (CBR Index)	67,94	%
Compressive strength at 28 days	3,74	Mpa
Chemical		
Methylene blue value	0,4	-

2.2 Method

2.2.1 Preparation Method

To determine the optimal mixing ratios of tuff and red brick waste (T-RBW), the red brick waste was first crushed and sieved through a 2 mm mesh (Fig. 1b). The tuff and red brick waste were then manually blended at four different proportions: 0%, 10%, 20%, and 30%. Each mixture was thoroughly homogenized by hand mixing for approximately 4–5 minutes to ensure a uniform distribution of the materials. After preparation, all mixtures were subjected to Modified Proctor compaction, California Bearing Ratio (CBR), and unconfined compressive strength (UCS) tests to evaluate their mechanical and physical properties. The mix design is summarized in Table 3.

2.2.2 Test Methods

Each test was performed on three replicate specimens to ensure the reliability and repeatability of the results. The UCS and CBR values reported in this study represent the average of the three test results. The data exhibited good consistency, with mean standard deviation (SD) values less than 10% of the mean (m) UCS or CBR values, confirming the reliability of the measurements.

All laboratory experiments were conducted under controlled environmental conditions to ensure accuracy and consistency. The specimens were tightly sealed in plastic bags to minimize moisture loss and stored in a controlled laboratory environment at a temperature of 23 ± 2 °C, which corresponds to the standard laboratory temperature commonly adopted in geotechnical and material testing. The relative humidity was kept at 50 ± 5%, and all specimens were stored and tested under these stable conditions prior to each experiment.

All experimental procedures were carried out in accordance with the French geotechnical standards (Norme Française – NF) to ensure methodological consistency and compliance with recognized testing protocols. Specifically, the Modified Proctor compaction test was performed according to NF P 94-093[42], the California Bearing Ratio (CBR) test followed the procedure described in NF P 94-078[43], and the Unconfined Compressive Strength (UCS) test was conducted in accordance with NF P 94-074[44], These standards are officially adopted in the laboratory where the experimental work was performed and provide reliable frameworks for evaluating soil compaction, bearing capacity, and strength characteristics.

Table 3. Various mixtures prepared T-RBW

Mixture	Tuff (T)	Red brick waste (RBW)
T-00RBW	100%	0%
T-10RBW	90%	10%
T-20RBW	80%	20%
T-30RBW	70%	30%

3. Results and Discussion

3.1. Compaction Behavior of the Mixture (T-RBW)

The compaction behavior of the tuff–red brick waste (T-RBW) mixtures was evaluated using the Modified Proctor test to determine the optimum moisture content (OMC) and maximum dry density (MDD) for each mixing ratio. The obtained compaction curves (Figure 5) demonstrate a progressive increase in dry density with increasing red brick waste content up to 20%, followed by a noticeable decrease at 30%.

Quantitatively, the maximum dry density (MDD) increased from 19.1 kN/m^3 for pure tuff (0% RBW) to 20.0 kN/m^3 at the 20% RBW mixture, representing an improvement of approximately 4.7%. Beyond this ratio, the MDD dropped to 18.3 kN/m^3 at 30% RBW. Similarly, the optimum moisture content (OMC) slightly increased from 10% for pure tuff to 10.6% at 20% RBW, indicating enhanced compact ability due to the addition of well-graded fine brick particles.

The increase in dry density up to the 20% RBW content can be attributed to improved particle packing and better gradation within the mixture. The grain size analysis of the natural tuff (Figure 3) revealed particle diameters ranging from 0.080 mm to 0.001 mm, each fraction contributing about 1–2% of the total weight. The inclusion of finely crushed red brick particles compensates for the deficiency of intermediate grain sizes in the tuff, resulting in denser packing and higher dry density. However, when the RBW content exceeds 20%, the excessive fine fraction reduces the material's permeability and increases water retention, leading to a decline in dry density.

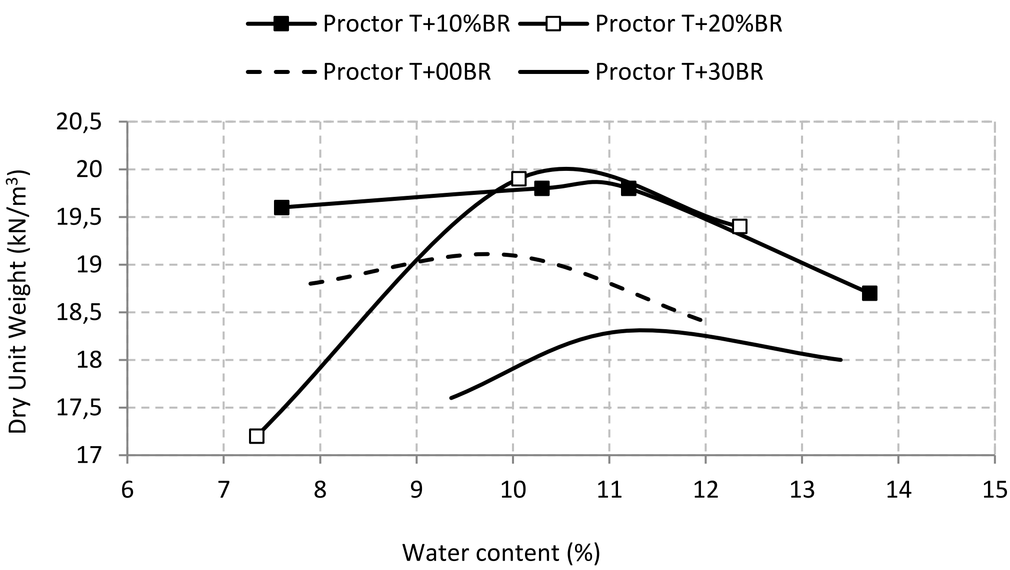

Fig. 5. Proctor curves of the various mixtures (T-BRW)

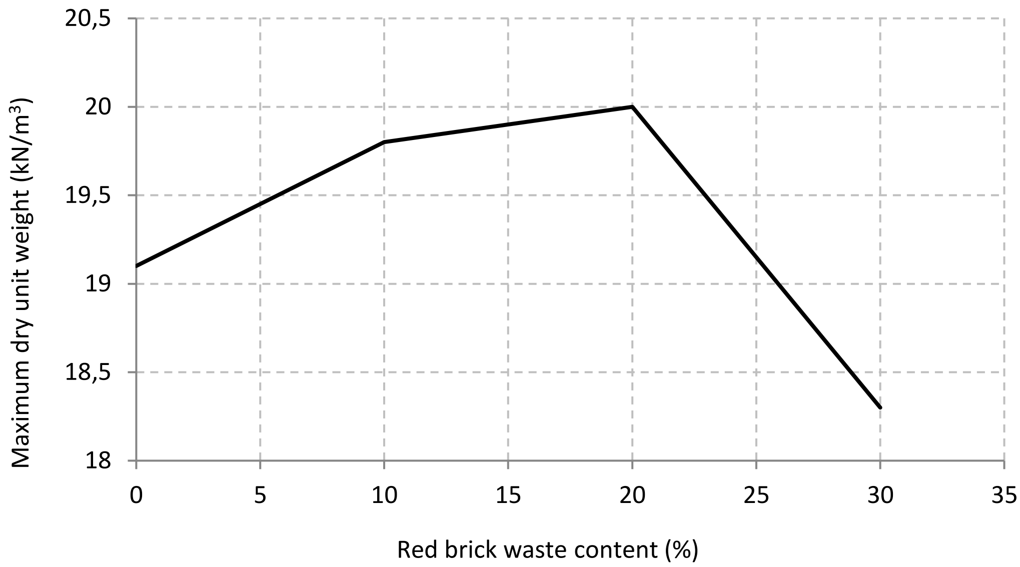

Fig. 6. Variation in dry density according to the percentage of RBW

3.2 Bearing Index Evolution

The bearing performance of the tuff–red brick waste (T-RBW) mixtures was assessed using the California Bearing Ratio (CBR) test, following the French standard NF P 94-078[43], The CBR index reflects the load-bearing capacity of compacted soils and is directly related to their density and moisture conditions. The obtained CBR results (Figures 7 and 8) show that the bearing capacity of the mixtures increases with the incorporation of red brick waste up to 20%, beyond which a slight decline is observed. Quantitatively, the CBR value of the natural tuff (0% RBW) was 67.94%, while the inclusion of 10% RBW increased it to 71.21%, and the 20% RBW mixture achieved the maximum CBR of 83.53%, representing an overall improvement of approximately 22.9% compared to the untreated soil.

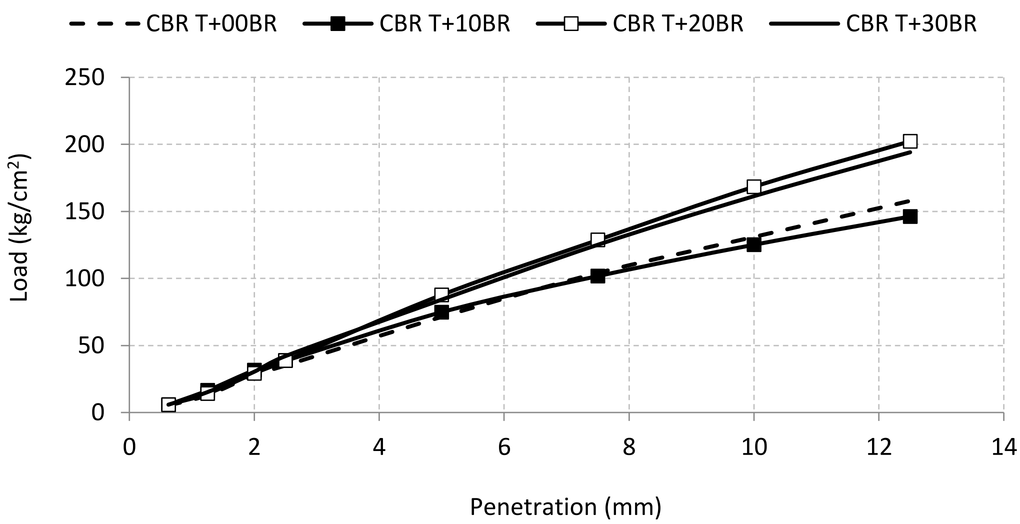

Fig. 7. Variation of piston pressure as a function of its depression for different compaction energies

When the red brick waste content was raised to 30%, the CBR slightly decreased to 80.19%, which still indicates a strong bearing capacity within the acceptable range for pavement sub-base materials. This improvement is primarily attributed to the enhanced interlocking and densification between the tuff particles and the crushed brick fines, which improve particle arrangement and load transfer efficiency under compaction. The reduction in CBR beyond 20% can be explained by the excessive fine fraction that hinders drainage and increases compressibility, thereby reducing load resistance. Overall, the results confirm that a 20% addition of red brick waste provides the most favorable balance between density and strength, optimizing the bearing performance of the T-RBW mixtures.

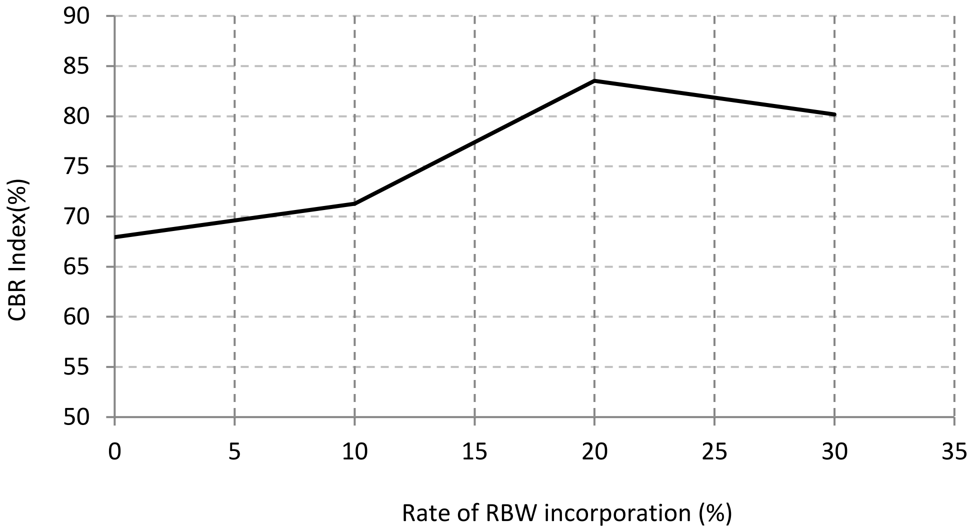

Fig. 8. Variation of the Bearing index of the mixtures (T-RBW) according to the percentage of RBW incorporated

3.3 Evolution of simple compressive strength (RC) of the mixture T-RBW

Compressive strength is a decisive criterion for selecting materials for desert pavement construction, and it was assessed using the unconfined compressive strength (UCS) procedure adapted from Fenzy [26]. The UCS apparatus used in this study is shown in Fig. 9, plus split cylindrical molds for specimen preparation.

Cylindrical specimens were prepared at the Proctor-determined optimum moisture content by blending tuff with red brick waste (RBW) at 0%, 10%, 20%, and 30%. For each blend, three replicate specimens were compacted into 50 mm × 100 mm molds to ensure repeatability. After molding, specimens were cured for 3, 7, 14, and 28 days before testing (Fig. 10a). Compression was then applied under a constant displacement rate of 1.04 mm/min on the UCS frame shown in Fig. 10b, allowing synchronized acquisition of axial load and strain to compute UCS and stiffness indices reliably.

Fig. 9. unconfined compressive strength (UCS) testing apparatus: load frame and split molds

(a)

(b)

Fig. 10. (a) Samples for different durations: 3, 7, 14, and 28 days and (b) The crushing of the test pieces

The results (Figures 11-12) show a consistent increase in compressive strength with the addition of RBW up to 20%, after which the strength decreases. Quantitatively, the UCS value increased from 3.74 MPa for pure tuff to 4.74 MPa at 10% RBW and reached its maximum of 5.05 MPa at 20% RBW representing a 35% improvement compared to untreated tuff. However, further addition to 30% RBW caused the UCS to drop to 2.80 MPa, likely due to excessive fine particles that reduce bonding and compactness.

The observed enhancement in compressive strength up to 20% RBW can be attributed to the improved particle interlock, better gradation, and higher compaction efficiency resulting from the inclusion of fine brick aggregates. The reduction beyond this percentage is associated with the increased proportion of fines, which disrupts the internal skeleton and reduces effective stress transfer. Overall, the results confirm that incorporating 20% red brick waste into tuff yields the optimum mechanical performance and can be considered an effective stabilization ratio for use in desert pavement base layers.

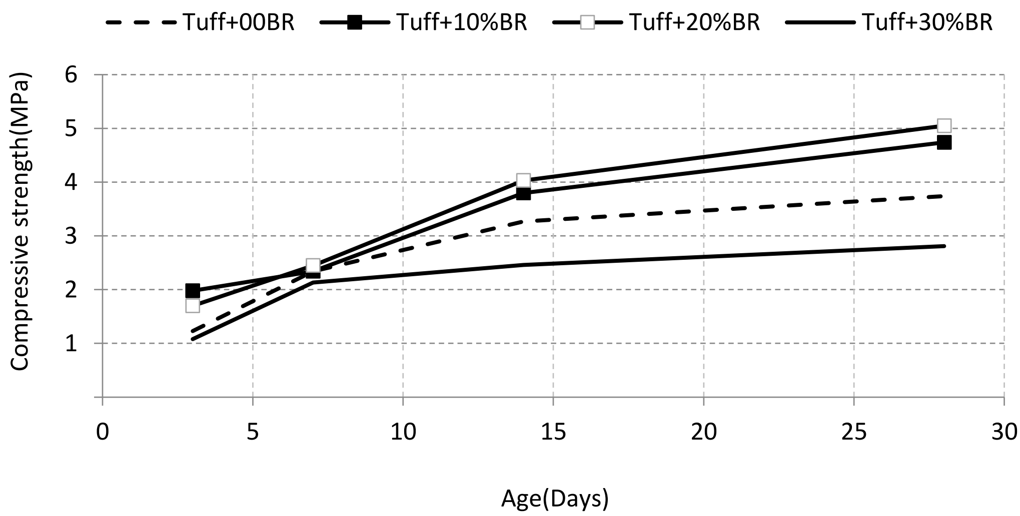

Fig 11. Effect of the age on the compressive strength of the mixes

The improvements in mechanical performance noted in this investigation are consistent with earlier studies about the use of tuff-based and recycled construction materials for geotechnical and pavement purposes. Akacem et al. (2020) [36] and Moulay Omar et al. (2022) [37] discovered that the addition of local tuff with dune sand increased compaction and increased unconfined compressive strength (UCS) due to the particles interlocking and a more favorable gradation. The current tuff–red brick waste (T-RBW) blends displayed comparable tendencies with a 20% replacement yield the highest dry density and UCS values. Cabalar and Omar [6] found the similar findings in the stabilization of silt with limestone powder in which dry density and UCS increased due to filler effects and better particle contact which is comparable with the densification behavior of T-RBW composites seen in this work.

Likewise, both Derabla and Bourema [13] and Saif et al. [15] showed that the addition of red brick waste debris to cementitious mixes enhances strength and provides longevity due the increasing internal packing and reduction in porosity. Several studies have emphasized the mechanical and environmental potential of other recycled construction debris, in addition to tuff-based products. For example, Arulrajah et al. [5] and Poon and Chan (2006) [18] looked at using crushed brick and recycled concrete aggregates in pavement subbases. They found that the CBR and UCS values were similar to those of natural materials. Babu and Durgarani [16] and Kaabeche and Belaoura [20] similarly showed that using recycled aggregates and industrial by-products like GGBS or ferrochrome slag can make pavement-quality concrete work better. This supports the broader sustainability context of the current research.

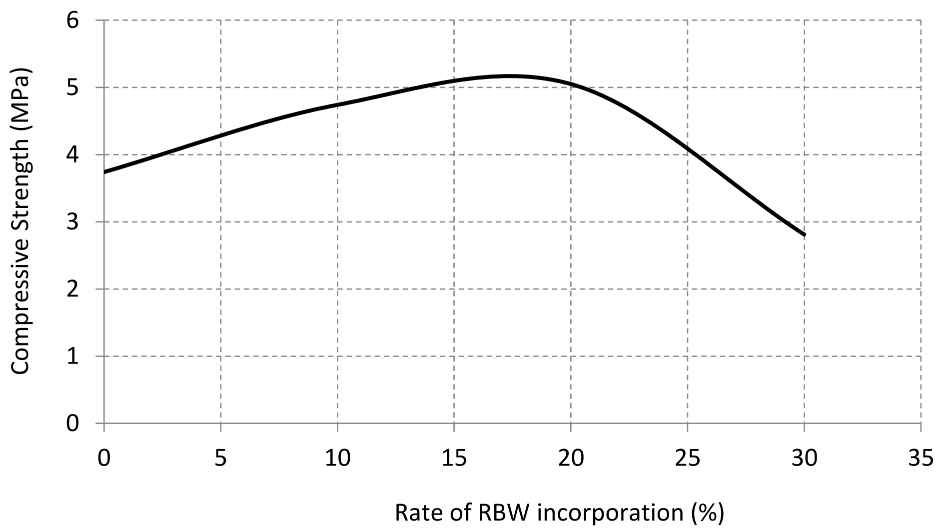

Fig 12. Red brick waste effect on the unconfined compressive strength of the mixes

Recent research (e.g., Deleprani et al., [1]; Safia Mebarek et al., [17]) has highlighted that recycled concrete powders and demolition waste can achieve superior mechanical performance while minimizing environmental impact, underscoring the significance of utilizing locally sourced materials like T-RBW. These results contribute to an expanding corpus of research advocating for circular economy tactics in the building industry. Overall, the current results confirm a consistent trend reported in the literature: mechanical parameters such as dry density, UCS, and CBR generally increase with the addition of fine recycled materials up to an optimal threshold (typically 20–30%), after which excessive fines may cause a slight reduction in performance. This trend emphasizes the mechanical dependability and sustainability potential of T-RBW composites for usage in subgrade and pavement layers, equivalent to other worldwide studies employing recycled concrete, steel slag, or calcareous additives.

4. Conclusion

The combination of tuff with red brick waste (RBW) gives a viable and sustainable alternative for minimizing reliance on non-renewable natural resources while addressing the environmental concerns faced by building waste disposal. Tuff, a volcanic material largely employed in desert road construction, is a non-renewable resource whose mining and transportation incur severe environmental and economic consequences. On the other hand, red brick waste, a result of demolition and construction activity, typically accumulates in huge amounts, adding to land

pollution and resource inefficiencies. Therefore, integrating RBW as a partial replacement for tuff not only mitigates these environmental problems but also corresponds with sustainable construction plans aimed at optimizing the use of locally accessible resources.
The experimental results of this investigation indicated an ideal mixture consisting of 80% tuff and 20% RBW, which displayed a substantial boost in mechanical performance. Specifically, the California Bearing Ratio (CBR) increased from 67.94% for tuff alone to 83.53% when mixed with RBW, suggesting higher load-bearing capacity suited for road foundation layers. Similarly, the unconfined compressive strength (UCS) exhibited a considerable rise from 3.74 MPa (tuff alone) to 5.05 MPa after 28 days of curing, demonstrating enhanced structural integrity and durability. Moreover, a combination made of 70% tuff and 30% RBW was determined to match the standard performance standards for desert road construction. Although this composition displayed a minor decrease in UCS to 2.8 MPa, it maintained a high CBR value of 80.19%, which is regarded as acceptable for such applications. This balance between mechanical performance and waste usage indicates the viability of using greater RBW replacement rates without compromising critical technical features.

In conclusion, the usage of tuff-RBW mixtures offers a dual benefit: preserving non-renewable resources and encouraging environmental sustainability by valorizing building waste. The findings argue for the implementation of these eco-friendly materials in desert road infrastructure projects, hence contributing to more sustainable and cost-effective construction procedures.

Future investigations should concentrate on enhancing the replacement ratios of red brick waste to 40% – 50% with the proportion of additives (i.e., cement, lime, fly ash, or pozzolanic materials) being up to a few percentages (i.e. 3–6%). With increased construction waste additives in the design, it provides an effective and permanent solution to remove it at a large scale while also reducing landfill disposal and promoting circularity of resources. Furthermore, thorough long-term durability assessments of moisture resistance, freeze–thaw and aging performance is recommended for all mixture proportions to verify the long-term compatibility and environmental sustainability of the T-RBW materials during actual field conditions.

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