

Research Article

Synergistic Effect of Pulverized Ceramic Waste and Crushed Granite on the Mechanical Performance of Ferrallitic Soil for Sustainable Pavement Applications

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Abstract

The valorization of construction waste to improve locally available geomaterials offers a promising approach to sustainable pavement construction. This study investigates the effects of pulverized ceramic waste (PCW) and crushed granite (CG) on the mechanical performance of ferrallitic soil from Tori-Dokanmey. Two series of mixtures were evaluated: soil stabilized with PCW alone and optimized mixtures incorporating both PCW and CG. Mechanical performance was assessed at different curing ages through compressive strength, three-point flexural tensile strength, secant modulus (E50), and static elastic modulus (Est). The results showed that PCW incorporation improved the long-term mechanical properties of the soil, primarily through enhanced particle packing and reduced internal porosity. Combining CG with PCW further improved performance by forming a denser granular skeleton and facilitating stress transfer within the material. Consequently, the optimized mixtures exhibited higher compressive and flexural strengths and greater stiffness than both untreated soil and mixtures stabilized with PCW alone. These findings highlight the complementary effects of CG and PCW and their potential to enhance locally available ferrallitic soil for pavement applications, while promoting construction waste valorization and the development of sustainable road materials in tropical regions.

Keywords

Ferrallitic Soil, Pulverized Ceramic Waste, Crushed Granite, Flexural Strength, Elastic Modulus, Sustainable Pavement

1. Introduction

The continuous expansion of road infrastructure in developing countries has considerably increased the demand for high-performance pavement materials. In tropical regions, lateritic soils are extensively used in road construction because of their widespread availability and low extraction costs.

However, many lateritic soils exhibit insufficient mechanical performance, including low strength and high susceptibility to deformation under traffic loading, which limits their direct use in pavement base and subbase layers [1]. Consequently, improving the mechanical behavior of these local materials has

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Received: 7 October 2026; **Accepted:** 15 October 2026; **Published:** 28 October 2026



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become a major challenge for sustainable road engineering.

Mechanical stabilization through the incorporation of granular materials and industrial by-products has emerged as an effective alternative to conventional chemical stabilizers. Among recycled materials, pulverized ceramic waste (PCW) has attracted increasing interest owing to its high silica and alumina contents, angular particle morphology and filler effect, which can enhance the compactness and strength of geomaterials [2]. Simultaneously, crushed granite (CG) is commonly employed to improve the particle-size distribution and skeleton structure of lateritic soils, leading to better particle interlocking and load transfer within the composite material [1].

Several studies have investigated the individual use of ceramic waste or crushed granite for improving the engineering properties of lateritic soils. Pulverized ceramic waste has been reported to reduce plasticity and improve strength through physical densification and, in the presence of hydraulic binders, pozzolanic reactions [2]. Likewise, crushed granite contributes to improving grading characteristics and increasing the bearing capacity of pavement materials [1]. Nevertheless, the combined influence of pulverized ceramic waste and crushed granite on the mechanical response of lateritic soils remains insufficiently documented.

Most previous investigations have mainly focused on conventional geotechnical indicators such as the California Bearing Ratio (CBR), compaction characteristics and unconfined compressive strength [1, 2]. Comparatively, limited attention has been devoted to the flexural performance and stiffness parameters of stabilized lateritic materials. Flexural strength, compressive strength, static elastic modulus and secant modulus provide complementary information on crack resistance, deformation capacity and structural stiffness, which are essential for evaluating the mechanical performance of pavement materials subjected to repeated traffic loading [2].

In this context, the present study investigates the influence of pulverized ceramic waste on the mechanical behavior of lateritic soil and evaluates the additional contribution of crushed granite through a comparative experimental approach. Two series of mixtures were examined: ferrallitic soil stabilized with pulverized ceramic waste (FS-PCW) and ferrallitic soil stabilized with pulverized ceramic waste and crushed granite (FS-PCW-CG) [1, 2]. Mechanical characterization was performed using flexural and compressive strength tests, from which the static elastic modulus and secant modulus were determined [2]. The comparative analysis aims to clarify the synergistic effect of pulverized ceramic waste and crushed granite and to identify an optimized formulation suitable for sustainable pavement applications.

2. Materials and Methods

2.1. Materials

2.1.1. Ferrallitic Soil

The soil sample from the bar that is the subject of our study comes from Tori-Dokanmey, a locality located in the municipality of Tori-Bossito, in southern Benin. Tori-Bossito is located in the Atlantic Department, approximately 40 kilometers northwest of Cotonou. Geographically, the municipality is bordered by Allada to the north, Ouidah to the south, Ze and Abomey-Calavi to the east, and Kpomasse to the west. It is located between latitudes 6°25' and 6°37' N and longitudes 2°01' and 2°17' E.

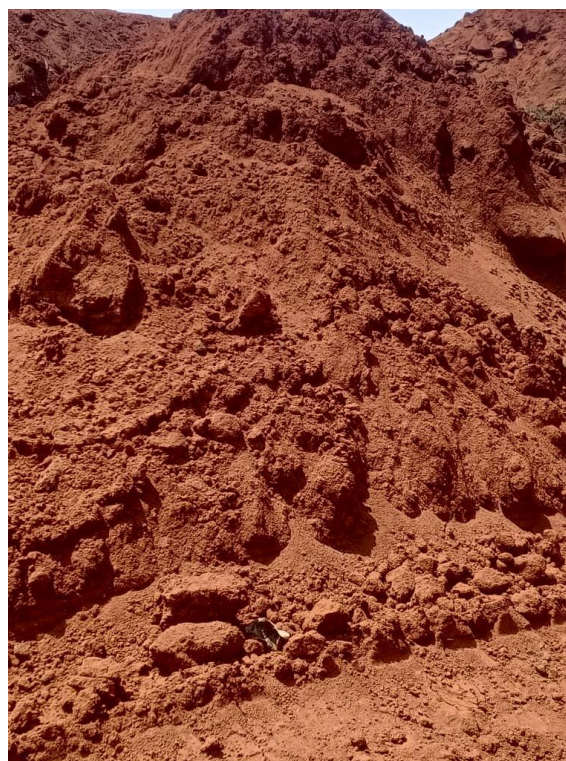


Figure 1. Ferrallitic soil.

The chemical analysis of the ferrallitic soil, locally known as “terre de barre,” indicates a predominance of silicon dioxide (SiO_2 : 62%) and aluminum oxide (Al_2O_3 : 24%), with smaller amounts of iron oxide (Fe_2O_3 : 2%), potassium oxide (K_2O : 1%), sodium oxide (Na_2O : 0.5%), calcium oxide (CaO : 0.3%), and magnesium oxide (MgO : 0.2%). The soil also contains approximately 10% structural water (H_2O). This composition is characteristic of highly weathered tropical soils, where intense leaching reduces the natural calcium content and enriches the clay fraction in silica and alumina. The high $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio (~ 2.6) confirms a kaolinitic nature, which imparts plasticity but limits natural cementation, making the

soil relatively weak in terms of mechanical performance if untreated.

Despite its low inherent cementitious potential, the silica and alumina content of terre de barre provides a favorable basis for stabilization via pozzolanic reactions. When combined with cement or other calcium sources, the reactive silica and alumina can interact with calcium hydroxide to form calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) phases, which densify the microstructure and improve compressive strength. The minor iron oxide content contributes to the formation of calcium aluminoferrite phases (C_4AF)

during cement hydration, slightly enhancing the binding capacity. Overall, the chemical characteristics of terre de barre justify its activation with cementitious materials to develop mechanically stable and durable composites suitable for road construction applications.

The results confirmed that the untreated soil has low bearing capacity and moderate plasticity, requiring stabilization to meet the technical specifications required for use in road construction.

Table 1. Geotechnical properties of the ferrallitic soil (sandy clayey soil) used in this study.

sandy clayey soil		Value	Standard deviation
Particle Size Distribution Analysis	Dmax (mm)	2	0
	2 mm (%)	100	0
	0.08 mm (%)	48	1
Atterberg limits	WL	54	1.01
	WP	32	1.73
	IP	22	2.3
Methylene blue value	VBS	1	0.01
Dry density	yd (g/cm ³)	1.9	0.26
Optimal water content	w _{opt} (%)	12.1	0.06
Maximum dry density	yd _{max} (g/cm ³)	2	0.1
CBR index (ICBR) after 96 hours of soaking	95% Opt	23	1.53
	100% Opt	41	1.52

Table 2. Chemical composition of bar soil.

Oxide	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	K ₂ O	Na ₂ O	CaO	MgO	H ₂ O structural
Estimated proportion (%)	62	24	2	1	0.5	0.3	0.2	10

2.1.2. Ceramic Waste

The ceramic waste (Figure 2a) used in this study was prepared through a controlled, multi-stage pulverization process. Initially, broken ceramic tile residues were collected from construction sites and waste disposal areas, followed by a sorting phase to eliminate non-ceramic impurities and retain only

clean, homogeneous fragments. These fragments were first crushed using a jaw crusher to reduce them to medium-sized particles. Subsequently, the material was finely pulverized using a hammer mill. The resulting powder was then sieved through a 0.08 mm mesh to isolate the fine fraction suitable for the experiments. Coarser particles retained on the sieve were reintroduced into the milling process to ensure uniform granulometry and consistency of the final product (Figure 2b).

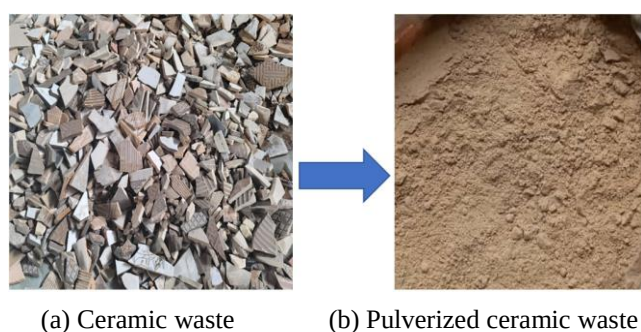


Figure 2. Ceramic waste.

The chemical composition of the pulverized ceramic waste (Table 3) is dominated by silicon dioxide (SiO_2 : 70%) and aluminum oxide (Al_2O_3 : 20%), with minor contents of Fe_2O_3 (2%), K_2O (3%), Na_2O (2%), CaO (1.2%), and MgO (0.8%). This silico-aluminous profile indicates a high pozzolanic potential, as the amorphous silica and alumina can react with calcium hydroxide released by cement hydration to form calcium silicate hydrates (C-S-H) and calcium aluminate hydrates (C-A-H), which enhance the strength and durability of the stabilized soil. The low natural calcium content confirms that the material is not self-cementitious and relies on external alkaline activation.

Table 3. Chemical composition of pulverized ceramic waste.

Oxide	SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	CaO	MgO
Estimated (%)	70	20	2	3	2	1.2	0.8

Minor oxides such as K_2O and Na_2O can increase the alkalinity of the pore solution, accelerating the dissolution of silica and alumina and improving the kinetics of pozzolanic reactions, while Fe_2O_3 may participate marginally in forming calcium aluminoferrite phases (C_4AF). Overall, the chemical composition demonstrates that pulverized ceramic waste is a suitable pozzolanic additive for enhancing the mechanical performance of clay-rich soils such as ferralitic “terre de barre,” offering a sustainable route for road construction stabilization through the valorization of local ceramic residues.

2.1.3. Granite Aggregates

In this study, the granite aggregates used were of 0/31.5 mm grading, sourced from the Dan quarry in the Republic of Benin. The village of Dan is situated in the municipality of Djidja, in the Zou Department, approximately 30 km from the city of Bohicon. Geographically, the municipality of Djidja lies between latitudes $7^\circ 10'$ and $7^\circ 40'$ North, and longitudes $1^\circ 04'$ and $2^\circ 10'$ East. The Dan quarry itself is located at $7^\circ 21' 44''$ N and $2^\circ 06' 38''$ E.

At this site, aggregates are extracted directly from massive granite outcrops using artisanal crushing techniques. The crushed materials are then screened and stockpiled according to their particle size distribution (Figure 3).



Figure 3. Granite Aggregates.

Table 4 summarizes the key geotechnical parameters of the granite aggregates sourced from the Dan quarry.

Table 4. Summary of the geotechnical characterization tests on 0/31.5 mm crushed granite aggregates.

N°	Particle Size Distribution Analysis			Sand equivalent: ES (%)	Methylene Blue Value (VBS)	Modified Proctor		CBR value after 96 hours of soaking			MDE (%)	LA (%)
	Maximum diameter: Dmax (mm)	D=2 mm (%)	D=0,08 mm (%)			Optimal water content: Ω_{opt} (%)	Optimal dry density: YOPM (g/cm3)	90% OPM (optimum)	95% OPM	100% OPM		
Test 1	31.5	28	12	55	0.15	8.2	2.2	51	76	102	6	22.7
Test 2	31.5	27	8	58	0.18	5.8	2.24	49	74	98	9	24
Test 3	31.5	28	9	60	0.16	6	2.3	45	71	99	9	24.2
Mean	31.5	27.7	9.7	57.7	0.16	6.67	2.25	48.3	73.7	99.7	8	23.6
Std Dev	0	0.6	2.1	2.52	0.015	1.33	0.05	3.06	2.52	2.08	1.73	0.81

2.2. Methods

2.2.1. Formulation Method

Two series of mixtures were designed to evaluate the influence of pulverized ceramic waste (PCW) on the mechanical performance of lateritic soil and the additional contribution of crushed granite (CG).

The first series consisted of ferralitic soil stabilized solely with pulverized ceramic waste (FS-PCW). The PCW content was progressively increased from 0 to 15 wt.% at intervals of 2.5 wt.%, replacing an equivalent mass of ferralitic soil. Seven mixtures (M1-M7) were prepared, including the untreated reference soil.

The second series was developed to investigate the combined effect of pulverized ceramic waste and crushed granite (FS-PCW-CG). In this series, the crushed granite content was varied from 10 to 25 wt.% (10, 15, 20 and 25 wt.%), while the PCW content was maintained at 7.5, 10 and 12.5 wt.%. The proportion of ferralitic soil was adjusted accordingly to ensure that the total mass of each mixture remained equal to 100%. Twelve formulations (M1-M12) were produced.

The compositions of both experimental series are presented in [Tables 5 and 6](#).

Table 5. Composition of FS-PCW mixtures.

Mixture	Ferralitic soil (%)	PCW (%)
M1	100.0	0.0
M2	97.5	2.5
M3	95.0	5.0
M4	92.5	7.5
M5	90.0	10.0
M6	87.5	12.5
M7	85.0	15.0

Table 6. Composition of FS-PCW-CG mixtures.

Mixture	Ferralitic soil (%)	PCW (%)	Crushed granite (%)
M1	82.5	7.5	10
M2	80.0	10.0	10
M3	77.5	12.5	10

Mixture	Ferralitic soil (%)	PCW (%)	Crushed granite (%)
M4	77.5	7.5	15
M5	75.0	10.0	15
M6	72.5	12.5	15
M7	72.5	7.5	20
M8	70.0	10.0	20
M9	67.5	12.5	20
M10	67.5	7.5	25
M11	65.0	10.0	25
M12	62.5	12.5	25

2.2.2. Sample Preparation

The preparation of the specimens followed a standardized procedure to ensure the reproducibility and homogeneity of all mixtures.

Drying: The ferralitic soil and pulverized ceramic waste were oven-dried at 50 °C until a constant mass was achieved.

Sieving: The dried materials were sieved to remove oversized particles and obtain a homogeneous grading before mixing.

Dry mixing: The ferralitic soil, pulverized ceramic waste and, where applicable, crushed granite were dry-mixed until a uniform color and texture were obtained.

Water addition: Water corresponding to the optimum moisture content determined from the Modified Proctor test was gradually added while continuously mixing to obtain a homogeneous mixture.

Specimen casting and compaction: The mixtures were compacted into prismatic molds according to the experimental protocol adopted in this study.

Curing: After demolding, the specimens were cured under controlled laboratory conditions until the designated testing ages.

Mechanical testing: Flexural and compressive strength tests were performed. The secant modulus (E_{50}) and static elastic modulus (E_{st}) were subsequently estimated using the strength-based correlations.

2.2.3. Determination of Mechanical Parameters (Compressive Strength, Flexural Strength) and Estimation of Secant and Static Modulus

The test specimens were prepared from mixtures of ferralitic soil (FS), pulverized ceramic waste (PCW), and crushed granite (CG), according to the formulations previously defined. After air drying, the materials were manually homogenized to ensure uniform distribution of binders and fine reactive particles. The optimum water content and maximum dry density were determined using the Modified Proctor method (NF EN 13286-2), which provides the most representative

compaction energy for road foundation materials. Compaction was carried out using a 25 kg rammer dropped from a height of 30 cm, delivering a unit energy of 73.6 J per blow. Each specimen was compacted in three layers with an equal number of blows per layer, reproducing a total compaction energy equivalent to the Modified Proctor test (~2575 J). This protocol ensures a uniform density representative of field compaction conditions for stabilized road materials.

The mixtures were molded into $4 \times 4 \times 16$ cm prisms (EN 1015-11), compacted layer by layer, demolded after 24 hours, and cured in a humid chamber at (20 ± 2) °C with a relative humidity above 95%. Curing durations of 7, 28, and 90 days were used, but the discussion focuses primarily on 28-day results, which are considered representative of the in-service mechanical performance of stabilized soils in road applications.

Mechanical testing included:

Unconfined compressive strength (R_c), determined on half-prisms ($4 \times 4 \times 8$ cm) according to EN 13286-41;

Flexural tensile strength (R_f), measured on full prisms ($4 \times 4 \times 16$ cm) in accordance with EN 1015-11;

Secant modulus of elasticity (E_{50}) and static modulus (E_{st}), both estimated from empirical correlations with R_c .

Numerous studies have examined the relationship between E_{50} and unconfined compressive strength (q_u) or (UCS), revealing that stiffness increases nonlinearly with strength. Topolnicki (2018) [4] reported that the E_{50} /UCS ratio varies from 50-300 for $UCS < 2.0$ MPa and 300-1000 for $UCS > 2.0$ MPa. Similar ranges have been reported by Terashi et al. (1980) [5], who reported $E_{50} = (75-1000) q_u$, Baker (2000) [6], who reported $E_{50} = (50-180) q_u$, and Bruce (2000) [7], who reported $E_{50} = (100-500) q_u$. Later, Masaki & Terashi (2013) [8] confirmed the interval $E_{50} = (350-1000) q_u$, while Filz & Navin (2006) [9] proposed an average design value of $E_{50} = 300 q_u$.

In this study, the empirical relationship proposed by Bruce et al. (2013) [10] was adopted, namely $E_{50} = 120 \times UCS$ for $UCS < 1.0$ MPa and $E_{50} = 380 \times UCS$ for $UCS > 1.0$ MPa. This formulation aligns closely with the correlation obtained by Bouchemella & Taibi (2022) [11] for unsaturated compacted clay-sand mixtures ($E_{50} = 156.73 \times q_u$, $R^2 = 0.9512$), particularly for low-strength ranges ($q_u < 1$ MPa). The close agreement between both correlations supports the use of Bouchemella & Taibi's expression as a realistic estimate of E_{50} for the stabilized Bar soil mixtures studied here.

To estimate the static modulus (E_{st}), representing the long-term deformation behavior, the empirical relationship proposed by CEBTP (1984) was used:

$$E_{st} = (1000-2000) R_c 7$$

The lower bound ($\approx 1000 \times R_c 7$) corresponds to highly plastic soils with greater deformability, while the upper bound ($\approx 2000 \times R_c 7$) applies to more granular, low-plasticity ma-

materials exhibiting higher stiffness. This range provides a rational framework linking early-age compressive strength (7 days) to long-term stiffness. For the mixtures studied—composed of moderately plastic Bar soil blended with granular and pozzolanic additives—an intermediate value ($\approx 1500 \times R_{c(7)}$) was considered representative.

Overall, this methodological approach enables the consistent estimation of both the instantaneous stiffness (E_{50}) and the long-term modulus (E_{st}), thus providing a comprehensive

understanding of the mechanical response of stabilized materials under load, representative of road foundation conditions.

The figure below (Figure 4) illustrates the different stages of the experimental process: sample preparation (Figure 4a), the rammer used for compaction (Figure 4b), the compaction process of the specimens (Figure 4c), the sealing of the specimens in plastic bags before curing to avoid moisture variations (Figure 4d), the unconfined compression test (Figure 4e), and the flexural tensile strength (Figure 4f).



(a): sample preparation

(b): rammer used for compaction (c): compaction process of the specimens



(d): sealing of the specimens in plastic bags before curing to avoid moisture variations (e): unconfined compression test (f): flexural tensile strength

Figure 4. Experimental process for specimen preparation and mechanical testing: (a) preparation of mixture; (b) rammer used for compaction; (c) specimen compaction process; (d) sealing of specimens in plastic bags before curing to prevent moisture variations; (e) the unconfined compression test; (f) the flexural tensile strength on $4 \times 4 \times 16$ cm prisms.

3. Results

3.1. Compressive Strength

The compressive strength of the lateritic soil-pulverized ceramic waste (LS-PCW) mixtures at 7, 28 and 90 days is presented in Figure 5. The results show that compressive strength is influenced by both PCW content and curing time, a trend consistent with observations in various stabilized and cementitious systems where strength development is a function of both mix composition and hydration period [12-14].

At 7 days, the compressive strength slightly decreased from

2.26 MPa for the untreated soil to 1.53 MPa for the mixture containing 15 wt.% PCW, indicating that the beneficial effect of PCW was not yet fully developed. Conversely, at 28 and 90 days, the compressive strength increased steadily with increasing PCW content, reaching 3.80 MPa and 5.90 MPa, respectively, compared with 1.98 MPa and 3.63 MPa for the untreated soil.

The long-term strength improvement can be attributed mainly to the filler effect of the fine ceramic particles, which enhanced particle packing, reduced porosity and improved stress transfer within the soil matrix [15-17]. The pozzolanic reactions, often cited for enhancing later-age strength in such materials, also contribute to this improvement [21-23]. The

mixture containing 15 wt.% PCW exhibited the highest compressive strength at 90 days, whereas the 12.5 wt.% mixture showed a slightly higher value at 28 days, indicating that the

strength response depended on both PCW content and curing age. [18-20].

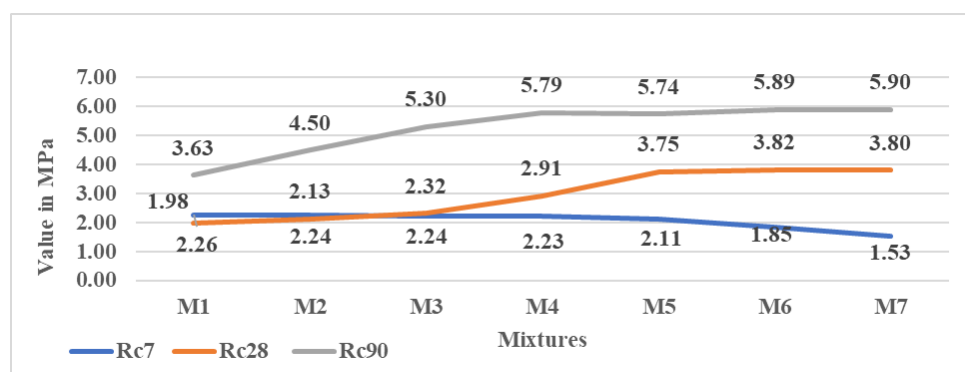


Figure 5. Compressive strength of Tori-Dokanmey ferrallitic soil -pulverized ceramic waste mixtures.

3.2. Three-point Flexural Tensile Strength

The three-point flexural tensile strength of the lateritic soil-pulverized ceramic waste (LS-PCW) mixtures at 7, 28 and 90 days is presented in Figure 6. The results indicate that both PCW content and curing time significantly influenced the tensile behavior, a trend that aligns with previous studies on the mechanical properties of stabilized soils and cementitious composites incorporating supplementary materials [13, 24-26].

At 7 days, the flexural tensile strength slightly decreased from 1.36 MPa for the untreated soil to 0.81 MPa for the mixture containing 15 wt.% PCW. In contrast, the strength progressively increased with curing time, reaching 1.01 MPa at

28 days and 2.16 MPa at 90 days, compared with 0.83 MPa and 1.17 MPa, respectively, for the untreated soil.

The long-term improvement is attributed to the filler effect of the fine ceramic particles, which enhanced particle packing, reduced porosity and improved interparticle bonding within the lateritic soil matrix [3, 17, 27]. This densification, combined with the pozzolanic activity of the ceramic waste over time, contributes to the enhanced mechanical performance observed at later ages [18]. The highest flexural tensile strength was obtained for mixtures containing 7.5-15 wt.% PCW, indicating an optimum stabilization range. These results confirm the potential of pulverized ceramic waste to enhance the tensile performance of lateritic soil for pavement applications.

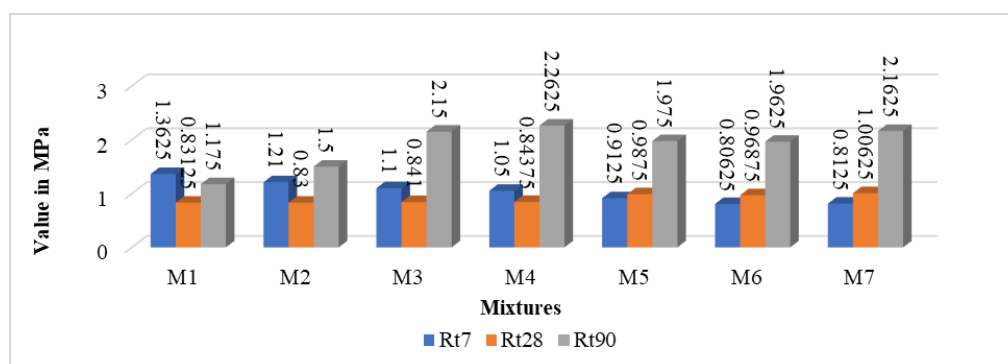


Figure 6. Three-point flexural tensile strength of Tori-Dokanmey ferrallitic soil -pulverized ceramic waste mixtures.

3.3. Secant and Static Elastic Modulus

The estimated secant modulus (E_{50}) and static elastic modulus (Est) of the lateritic soil-pulverized ceramic waste (LS-

PCW) mixtures are presented in Figure 7. The results reveal opposite trends with increasing PCW content.

The secant modulus (E_{50}) increased progressively from 752.9 MPa for the untreated soil to 1451.9 MPa at 12.5 wt.% PCW, before slightly decreasing to 1442.4 MPa at 15 wt.%

PCW. This increase indicates an improvement in the material stiffness at intermediate loading levels, which can be attributed to enhanced particle packing and reduced pore volume.

Conversely, the static elastic modulus (Est) gradually decreased from 3384.4 MPa for the untreated soil to 2300.0 MPa at 15 wt.% PCW, suggesting a reduction in the overall stiffness under full loading conditions. This behavior may result from changes in the balance between the granular skeleton and

the fine ceramic fraction as the PCW content increases.

The estimated E50 and Est values reflect the compressive strengths measured at 28 and 7 days, respectively, rather than independent stiffness measurements. Although approximately 12.5 wt.% PCW yielded the highest estimated E50, the contrasting trends across mechanical responses do not establish a unique optimum dosage or demonstrate distinct deformation mechanisms.

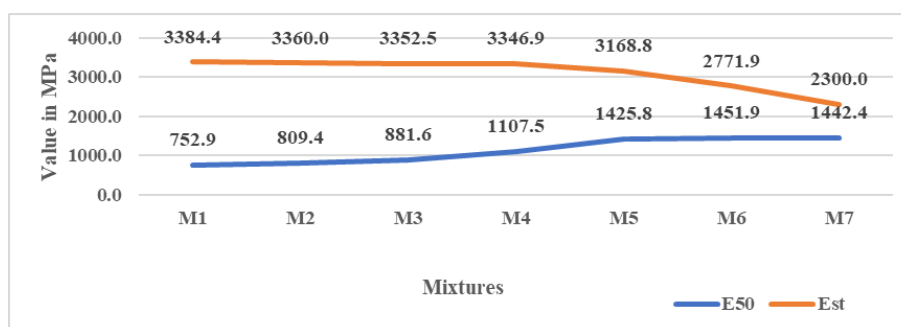


Figure 7. Secant and static elastic moduli of Tori-Dokanmey ferralitic soil-pulverized ceramic waste mixtures.

3.4. Compressive Strength of the Optimized LS-PCW-CG Mixtures

The compressive strength of the optimized lateritic soil-pulverized ceramic waste-crushed granite (LS-PCW-CG) mixtures is presented in Figure 8. For all formulations, the compressive strength increased with curing time ($R_{c7} < R_{c28} < R_{c90}$), indicating a progressive improvement in the mechanical performance of the stabilized mixtures.

A significant increase in compressive strength was observed from the reference mixture (M1) to the optimum mixture (M12), with an improvement exceeding 60% after 90 days of curing. This enhancement is mainly attributed to the combined effect of crushed granite, which strengthens the granular skeleton, and pulverized ceramic waste, which improves particle packing and reduces pore volume through a filler effect.

Overall, the combined CG-PCW mixtures exhibited promising compressive strengths under the investigated laboratory conditions. These findings support further evaluation for potential pavement applications, but do not establish synergy, an optimum formulation, or quantified sustainability benefits.

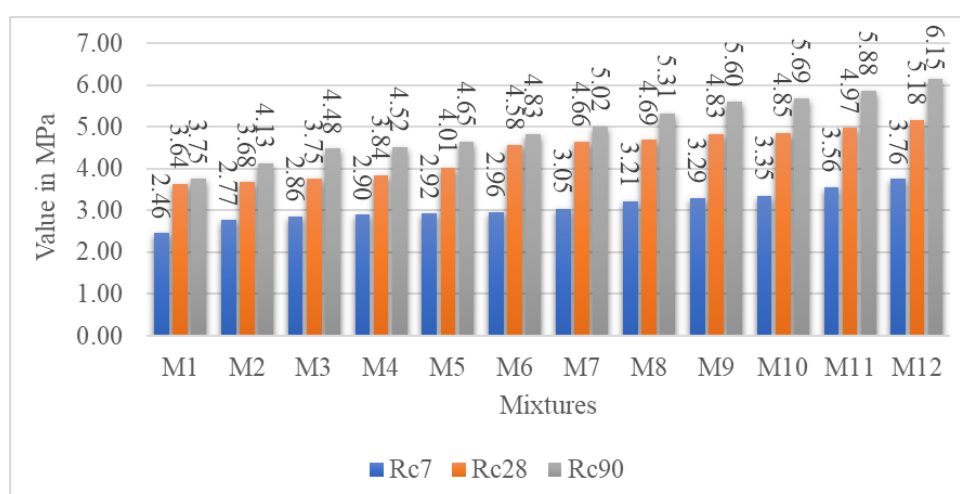


Figure 8. Compressive strength of ferralitic soil stabilized with crushed granite and pulverized ceramic waste.

3.5. Three-point Flexural Tensile Strength of the Optimized LS-PCW-CG Mixtures

The three-point flexural tensile strength of the optimized lateritic soil-pulverized ceramic waste-crushed granite (LS-PCW-CG) mixtures is presented in Figure 9. The results show a continuous increase in tensile strength with curing time ($R_{t7} < R_{t28} < R_{t90}$) for all mixtures, indicating the progressive development of the mechanical properties.

Compared with the reference mixture, the optimized formulations exhibited strength gains exceeding 70% after 90 days

of curing. This improvement is mainly attributed to the synergistic effect of crushed granite and pulverized ceramic waste. Crushed granite enhances the granular skeleton and load transfer, whereas the fine ceramic particles improve particle packing and reduce pore volume, resulting in a denser and more homogeneous matrix.

The combined incorporation of crushed granite and pulverized ceramic waste improved the measured flexural strength under the investigated laboratory conditions. This improvement reflects greater resistance to monotonic bending, without establishing cracking resistance under repeated loading or suitability for pavement applications.

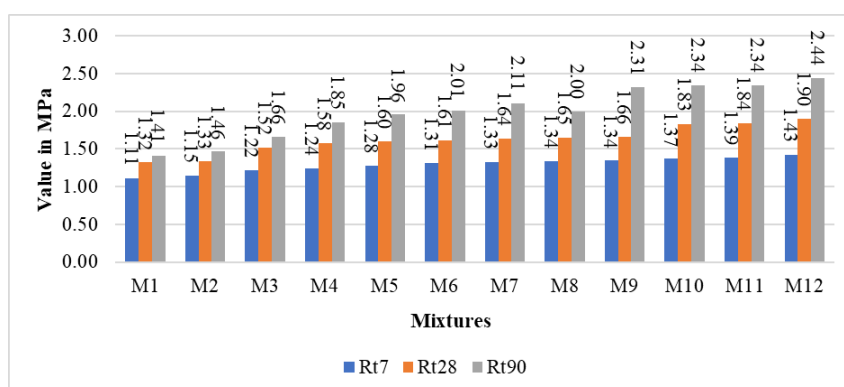


Figure 9. Three-point flexural tensile strength of ferralitic soil -crushed granite-pulverized ceramic waste mixtures.

3.6. Secant and Static Elastic Moduli of the Optimized Ls-Pcw-Cg Mixtures

The estimated secant modulus (E_{50}) and static elastic modulus (E_{st}) of the optimized lateritic soil-pulverized ceramic waste-crushed granite (LS-PCW-CG) mixtures are presented in Figure 10. Both moduli increased with the incorporation of crushed granite and pulverized ceramic waste. The secant modulus increased from 1383 MPa to 1966 MPa, while the static elastic modulus increased from 3687 MPa to 5634 MPa,

indicating a significant improvement in material stiffness.

The increase in stiffness is consistent with the compressive strength results and can be attributed to the synergistic effect of crushed granite, which reinforces the granular skeleton, and pulverized ceramic waste, which enhances particle packing and reduces pore volume. As expected, E_{st} remained consistently higher than E_{50} , reflecting the difference between the initial elastic response and the secant stiffness under loading. Overall, the optimized LS-PCW-CG mixtures exhibited enhanced stiffness, demonstrating their suitability for pavement applications.

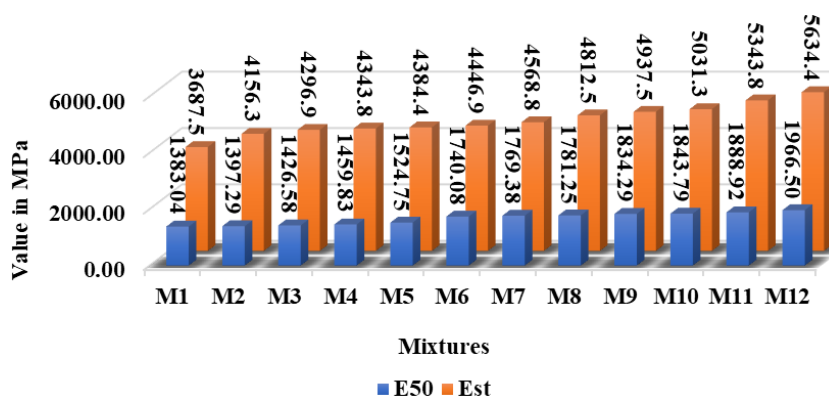


Figure 10. Secant and static elastic moduli of Tori-Dokanmey ferralitic soil -crushed granite-pulverized ceramic waste mixtures.

4. Discussion

The mechanical performance of Tori-Dokanmey ferralitic soil was significantly influenced by the incorporation of pulverized ceramic waste (PCW) and crushed granite (CG). The results obtained from compressive strength, three-point flexural tensile strength, secant modulus (E50) and static elastic modulus (Est) demonstrate that the combined stabilization approach provides a more effective improvement than the use of PCW alone.

For the FS-PCW mixtures, the progressive increase in mechanical properties with curing time highlights the beneficial role of ceramic waste in modifying the soil structure. At early curing ages, the limited improvement can be associated with the predominant physical effects of PCW incorporation, particularly particle rearrangement and filler action. With increasing curing time, the finer ceramic particles contribute to a denser particle arrangement by filling the voids between soil grains, reducing internal porosity and improving stress transfer within the matrix. This explains the continuous increase in compressive and flexural strengths observed at 28 and 90 days.

The incorporation of crushed granite in the FS-PCW-CG mixtures resulted in a further improvement in mechanical performance. Unlike the fine ceramic fraction, crushed granite acts mainly as a coarse granular skeleton that enhances load-bearing capacity through improved particle interlocking and better stress distribution. The simultaneous presence of CG and PCW therefore creates a complementary effect: crushed granite provides structural stability, while ceramic particles improve matrix continuity by reducing void spaces. This synergistic mechanism explains the higher compressive strength, flexural tensile strength and stiffness values obtained for the optimized mixtures.

The evolution of the elastic parameters confirms this improvement in mechanical behavior. The increase in E50 indicates a higher resistance to deformation under intermediate loading conditions, which is particularly relevant for pavement materials subjected to repeated traffic stresses. Although Est and E50 characterize different deformation ranges, their simultaneous increase in the optimized mixtures indicates an overall enhancement of material rigidity and structural integrity.

The improvement in flexural tensile strength is particularly significant for pavement applications, as tensile stresses generated by traffic loading and environmental variations may lead to crack initiation. The combined stabilization reduces structural discontinuities and improves the cohesion of the soil matrix, resulting in better crack resistance. Consequently, the optimized FS-PCW-CG mixtures exhibit a more balanced mechanical behavior compared with untreated soil and PCW-stabilized mixtures.

These findings highlight the importance of optimizing the proportion between fine recycled ceramic particles and coarse granite aggregates. Excessive fine material may modify the

soil skeleton and limit stiffness improvement, whereas an appropriate combination of PCW and CG promotes better packing density and mechanical performance. Therefore, the synergistic incorporation of pulverized ceramic waste and crushed granite represents an effective strategy for transforming locally available lateritic soil into a high-performance and sustainable pavement material.

5. Conclusions

This study investigated the effect of pulverized ceramic waste (PCW) and crushed granite (CG) incorporation on the mechanical performance of Tori-Dokanmey ferralitic soil for sustainable pavement applications. Two stabilization approaches were evaluated: ferralitic soil stabilized with PCW alone and lateritic soil stabilized with a combination of PCW and CG.

The results demonstrated that the incorporation of PCW improved the long-term mechanical behavior of the ferralitic soil. Although the initial strength development was limited at early curing ages, significant improvements were observed at 28 and 90 days, mainly due to enhanced particle packing, reduced void volume and improved interparticle interactions within the soil matrix.

The addition of crushed granite further enhanced the performance of the PCW-stabilized soil by providing a stronger granular skeleton and improving load transfer mechanisms. The optimized FS-PCW-CG mixtures exhibited higher compressive strength, flexural tensile strength and stiffness parameters compared with the untreated soil and FS-PCW mixtures, confirming the synergistic effect between coarse granite particles and fine ceramic waste particles.

The evolution of the secant modulus (E50) and static elastic modulus (Est) revealed a significant improvement in deformation resistance, indicating a more rigid and stable material structure suitable for pavement layers subjected to mechanical loading.

Overall, the combined use of pulverized ceramic waste and crushed granite provides an effective and sustainable approach for improving the engineering performance of locally available ferralitic soil. This strategy contributes to the valorization of ceramic waste, reduces dependence on conventional aggregates and promotes the development of environmentally friendly pavement materials in tropical regions.

Further investigations involving microstructural characterization and durability assessment are recommended to better understand the long-term behavior of these optimized mixtures under field conditions.

Abbreviations

PCW	Pulverized Ceramic Waste
CG	Crushed Granite

LS Lateritic Soil

Acknowledgments

The authors would like to thank all the laboratory technicians at the *Laboratory of Applied Energy and Mechanics (LEMA)*, University of Abomey-Calavi (UAC), Benin; at *SNERTP* (National Society for Testing and Research in Public Works); and at *X-TECHLAB*, Seme City, Benin, for their consistent support and technical assistance in performing the geotechnical, mineralogical, and mechanical tests.

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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