

Experimental Evaluation of Lateritic Sub-Base Soil Stabilized with Cement and Charcoal

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ABSTRACT: Premature pavement failures in Nigeria are often linked to weak lateritic subgrades, which typically show high plasticity and soaked CBR below 10%. Cement stabilization is effective but costly and carbon-intensive at high dosage, and little evidence exists on using Iroko Wood Charcoal (IWC) as a partial cement replacement. This study stabilized a lateritic soil from Ibadan with nine blends of 0–6% CEM I Portland cement and 0–6% IWC, evaluating index properties, compaction, 24-hour soaked CBR, and Unconfined Compressive Strength (UCS) at 3 and 7 days. The 6% cement, 2% IWC blend produced the lowest plasticity index, highest CBR (15.63%), and highest UCS (313.27 kPa), a sixteen-fold strength gain over the untreated soil, before performance declined beyond 2% IWC due to the charcoal's high water demand. This optimum blend exceeded the general subgrade CBR requirement of 10% but fell short of the Federal Ministry of Works and Housing (FMWH) stabilized sub-base thresholds for CBR and UCS. The stabilization is therefore suited to lower-tier applications, meaning pavement layers placed below the sub-base, such as improved subgrade and capping layers, that require a soaked CBR of at least 10%. Only 6% cement with 2% IWC (15.63%) or 4% IWC (15.56%) reached this level, and higher binder content is needed for full sub-base compliance.

KEYWORDS: Lateritic soil, soil stabilization, Iroko wood charcoal, cement, California Bearing Ratio, unconfined compressive strength

1. INTRODUCTION

Premature failure of flexible pavements remains a widespread challenge on Nigerian roads, and is frequently traced to inadequate subgrade strength rather than to deficiencies in the pavement structure itself [1]. Many of the lateritic soils used as subgrade material across South-West Nigeria exhibit high plasticity indices and low soaked California Bearing Ratio (CBR) values, often below the 10% minimum recommended for subgrade service, leaving pavements vulnerable to deformation and cracking once exposed to repeated traffic loading and seasonal moisture variation [2].

Cement stabilization is a well-established remedy for such deficiencies, reliably improving the strength and plasticity characteristics of weak lateritic soils. However, CEM I Portland cement is costly relative to the scale of road construction required in developing economies, making high-dosage cement stabilization increasingly difficult to justify on economic grounds [3]. This has motivated growing interest in agro-industrial by-products as partial cement replacements, several of which have shown pozzolanic or filler activity capable of supplementing cement's stabilizing action at lower overall binder cost [4], [5].

Iroko (*Milicia excelsa*) is a dense hardwood widely available in South-West Nigeria, and charcoal produced from its offcuts represents a low-cost, locally sourced by-product with a highly porous, high-surface-area particle structure known to influence the physical and chemical properties of soils it is

blended with [6]. Despite this potential, there is limited experimental evidence on whether Iroko Wood Charcoal (IWC), used alongside CEM I Portland cement, can improve the geotechnical performance of lateritic sub-base soil sufficiently to meet the requirements of the Federal Ministry of Works and Housing (FMWH) [7] for stabilized subgrade or sub-base material. This study addresses that gap directly, through a systematic laboratory investigation of a lateritic soil stabilized with combinations of cement and IWC.

The aim of the study was to investigate the synergistic effects of IWC and CEM I Portland cement on the geotechnical properties of a lateritic sub-base soil, and to evaluate the suitability of the resulting blends for road construction in accordance with FMWH requirements [7]. The specific objectives were to: (a) characterize the physical properties of the natural soil, cement, and IWC; (b) determine the mix proportions yielding the greatest improvement in soil stability; (c) quantify the effect of the stabilizers on CBR, Unconfined Compressive Strength (UCS), and compaction characteristics; and (d) assess the compliance of the optimum blend with FMWH specifications for stabilized subgrade and sub-base material.

2. MATERIALS AND METHODS

2.1. Materials

The lateritic soil used in this study was sourced from Cultural Centre Road, Ibadan, Oyo State, Nigeria, at a depth below the topsoil layer to obtain material representative of sub-

base conditions (Fig. 1). CEM I Portland cement conforming to relevant Nigerian Industrial Standards was used as the primary binder, and Iroko Wood Charcoal was obtained from sawmill offcuts, air-dried, and pulverized to pass the sieve size used for the parent soil prior to blending.



Fig. 1. Location of the soil sampling site on Cultural Centre Road, Ibadan, Oyo State, Nigeria.

2.2. Mix Design

A control specimen and eight cement-IWC combinations were prepared, using cement contents of 3% and 6% and IWC contents of 0%, 2%, 4%, and 6%, all expressed as a percentage of dry soil weight. The nine mixes, designated M1 to M9, are summarized in Table 1.

Table 1. Stabilization mix design matrix (M1–M9).

Mix ID	Cement (%)	IWC (%)	Description
M1	0	0	Control
M2	3	0	Cement only

M3	3	2	Low C + Low IWC
M4	3	4	Low C + Mod. IWC
M5	3	6	Low C + High IWC
M6	6	0	High C only
M7	6	2	High C + Low IWC
M8	6	4	High C + Mod. IWC
M9	6	6	High C + High IWC

2.3. Testing Programme

Natural moisture content (ASTM D2216 [8]) and specific gravity were determined for the natural soil, and particle size distribution (ASTM D422 [9]) was obtained by mechanical sieving. Atterberg limit testing (ASTM D4318 [10]) was carried out on the control soil and all eight stabilized blends to obtain the Liquid Limit, Plastic Limit, and Plasticity Index of each mix. Modified Proctor compaction testing (ASTM D1557 [11]) established the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) of every mix. California Bearing Ratio testing (ASTM D1883 [12]) was carried out under a 24-hour soaked condition representative of sub-base service, with penetration resistance recorded from both the top and bottom faces of each mould at 2.5 mm and 5.0 mm penetration. Unconfined Compressive Strength testing (ASTM D2166 [13]) was carried out on cylindrical specimens (95 mm height, 50 mm diameter) cured for 3 and 7 days, with peak axial stress computed from the recorded load using the corrected cross-sectional area method. All apparatus and procedures conformed additionally to the relevant parts of BS 1377:1990 [14] where applicable.

The CBR value at each penetration depth was calculated as:

$$CBR (\%) = (Test Load / Standard Load) \times 100 \quad (1)$$

using standard loads of 13.24 kN and 19.96 kN at 2.5 mm and 5.0 mm penetration respectively, and the Unconfined Compressive Strength was calculated as:

$$q_u = P / A_c \quad (2)$$

where P is the maximum applied load and A_c is the corrected cross-sectional area of the specimen at failure.

3. RESULTS AND DISCUSSION

3.1. Physical and Index Properties of the Natural Soil

The natural soil recorded an average natural moisture content of 4.82% and a specific gravity of 2.68. Sieve analysis showed a predominantly sandy gradation, comprising 8.3% gravel, 90.7% sand, and only 1.0% fines, with a coefficient of uniformity of 5.52 and a coefficient of curvature of 1.46, classifying the soil as well-graded sand (SW/SW-SM) under

USCS and as A-1-b under AASHTO. The control specimen returned a Liquid Limit of 29.87%, a Plastic Limit of 22.24%, and a Plasticity Index of 7.63%, consistent with a low-plasticity, granular lateritic material [1], [2].

3.2. Atterberg Limits of the Stabilized Blends

Cement addition alone reduced the Plasticity Index from 7.63% to 5.90% at 3% cement and to 4.70% at 6% cement, consistent with cation exchange and flocculation of the fine fraction [4]. The lowest Plasticity Index recorded across all nine mixes, 3.50%, occurred in Mix M7 (6% cement, 2% IWC). Beyond 2% IWC, the Liquid Limit rebounded and the Plasticity Index partially recovered, an effect attributed to the high intra-particle porosity and water-adsorption capacity of the charcoal [6] outweighing the flocculating action of the cement at higher inclusion rates.

3.3. Compaction Characteristics

The untreated soil achieved a Maximum Dry Density of 1.83 g/cm³ at an Optimum Moisture Content of 10.40%. Mix M3 (3% cement, 2% IWC) recorded the highest density of any mix, 1.87 g/cm³, at the lowest Optimum Moisture Content, 8.48%, reflecting efficient particle packing at this proportion. Density declined progressively beyond 2% IWC, falling to a minimum of 1.69 g/cm³ in Mixes M8 and M9, consistent with the lower specific gravity of charcoal relative to the mineral soil solids it displaces.

3.4. California Bearing Ratio

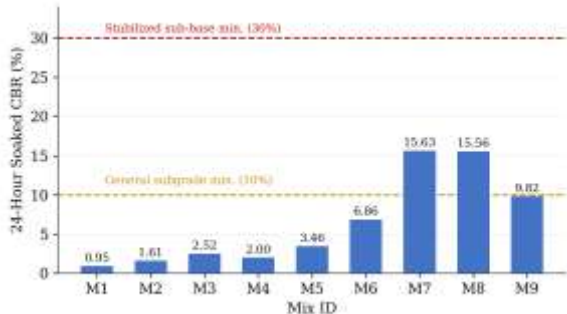


Fig. 2. Variation of 24-hour soaked CBR across Mix Blends M1–M9, with FMWH general subgrade and stabilized sub-base thresholds indicated.

The untreated soil recorded a soaked CBR of only 0.95%. Stabilization produced substantial improvement at the 6% cement level, where CBR reached 15.63% in Mix M7 and 15.56% in Mix M8, before declining to 9.82% in Mix M9. Mix M7 therefore achieved the highest soaked CBR recorded in the study, an approximately sixteen-fold improvement over the untreated control. Mixes M7 and M8 were the only blends to exceed the 10% soaked CBR required for subgrade service [7].

3.5. Unconfined Compressive Strength

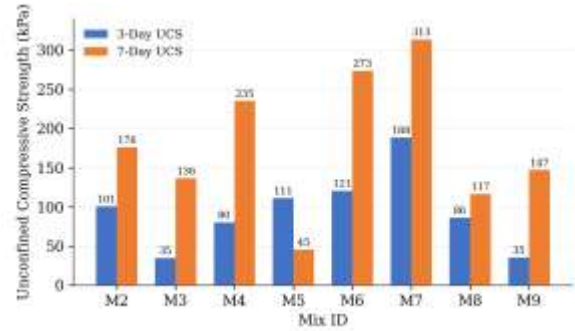


Fig. 3. Comparison of 3-day and 7-day Unconfined Compressive Strength across Mix Blends M2–M9.

Peak axial stress increased markedly between 3 and 7 days of curing for seven of the eight stabilized blends, consistent with continued cement hydration. Mix M7 again recorded the highest strength among the mixes tested, at 188.33 kPa (3 days) and 313.27 kPa (7 days), followed by Mix M6 (6% cement, 0% IWC) at 273.48 kPa at 7 days.

3.6. Optimum Blend and Compliance with Federal Ministry of Works and Housing (FMWH) Requirements

Taking plasticity, compaction, and strength results together, Mix M7 (6% cement, 2% IWC) was identified as the most consistently effective blend investigated, recording the lowest Plasticity Index, the highest soaked CBR, and the highest UCS at both curing ages among the nine mixes tested. Table 2 compares Mix M7 against the Federal Ministry of Works and Housing (FMWH) requirements for stabilized sub-base material [7].

Table 2. Compliance of the optimum blend (M7) with Federal Ministry of Works and Housing (FMWH) requirements [7].

Criterion	FMWH Stabilized Requirement	Mix M7 Result
% Passing No.200	—	1.0%
Liquid Limit	≤ 35%	28.20%
Plasticity Index	≤ 12%	3.50%
CBR, Soaked	≥ 30%	15.63%
UCS, 7 days	1.5–3.0 N/mm ²	0.313 N/mm ²

Mix M7 satisfied the fines, Liquid Limit, and Plasticity Index criteria, and its soaked CBR of 15.63% exceeded the general subgrade requirement of 10% [7]. However, it fell short of the stricter 30% soaked CBR threshold specified for stabilized sub-base material, and its 7-day UCS of 0.313 N/mm² fell far short of the 1.5–3.0 N/mm² range required for stabilized sub-base material, achieving only approximately one-fifth of the minimum requirement. Within the range of binder

proportions investigated, cement-charcoal stabilization therefore did not achieve full compliance with FMWH requirements for a stabilized sub-base course, notwithstanding the substantial improvement over the untreated soil.

4. CONCLUSION

This study demonstrated that Iroko Wood Charcoal, used alongside CEM I Portland cement, can measurably improve the plasticity, compaction, and strength characteristics of a lateritic sub-base soil, with a 2% IWC inclusion rate identified as the threshold beyond which the charcoal's water-adsorption behaviour begins to outweigh its beneficial filler action. The optimum blend identified, 6% cement with 2% IWC, achieved a sixteen-fold improvement in soaked CBR and the highest UCS of all mixes tested, exceeding the general FMWH subgrade CBR requirement, but falling short of the stricter requirements specified for stabilized sub-base material on both CBR and UCS grounds. The results indicate that cement-IWC stabilization, at the proportions investigated, is best suited to lower-tier applications. In this study, lower-tier applications means pavement layers placed below the sub-base, such as capping layers and improved subgrade, for which a soaked CBR of at least 10% is required [7]. Only 6% cement with 2% IWC (M7, 15.63%) or 4% IWC (M8, 15.56%) met this level, 6% cement with 6% IWC (M9, 9.82%) fell just short, and none of the 3% cement blends (1.61–3.46%) qualified. Higher cement content or extended curing would be required to achieve full sub-base compliance.

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REFERENCES

1. S. A. Ola, *Tropical Soils of Nigeria in Engineering Practice*. Rotterdam, Netherlands: A. A. Balkema, 1983.
2. M. D. Gidigasu, *Laterite Soil Engineering: Pedogenesis and Engineering Principles*. Amsterdam, Netherlands: Elsevier, 1976.
3. S. M. V. S. P. Kumar, L. D. Prasad, Ch. S. Rayana, and D. S. V. Prasad, “A study on stabilization of expansive soil by using agricultural by-products (RHA & SCBA),” *Int. J. Civil Eng.*, vol. 5, no. 8, pp. 17–21, 2018.
4. K. C. Onyelowe, “Cement stabilized palm kernel shell ash as a modifier for lateritic soil,” *Int. J. Sci. Eng.*, 2012.
5. G. O. Adunoye, K. T. Oladepo, I. Yinusa, and D. E. Chibuogwu, “Effects of lime on bagasse ash-stabilised expansive soils,” *African J. Environ. Nat. Sci. Res.*, vol. 7, no. 2, pp. 84–92, 2024.

6. A. T. Ogundele, “Assessment of impacts of charcoal production on soil properties in parts of the Nigerian savanna,” *J. Soil Sci. Environ. Manage.*, 2011.
7. Federal Ministry of Works and Housing, *General Specification for Roads and Bridges*, vol. II. Abuja, Nigeria, 1997.
8. ASTM D2216, *Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass*. West Conshohocken, PA: ASTM International.
9. ASTM D422, *Standard Test Method for Particle-Size Analysis of Soils*. West Conshohocken, PA: ASTM International.
10. ASTM D4318, *Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils*. West Conshohocken, PA: ASTM International.
11. ASTM D1557, *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort*. West Conshohocken, PA: ASTM International.
12. ASTM D1883, *Standard Test Method for California Bearing Ratio (CBR) of Laboratory-Compacted Soils*. West Conshohocken, PA: ASTM International.
13. ASTM D2166, *Standard Test Method for Unconfined Compressive Strength of Cohesive Soil*. West Conshohocken, PA: ASTM International.
14. British Standards Institution, *BS 1377:1990, Methods of Test for Soils for Civil Engineering Purposes*. London, U.K.: BSI, 1990.