Uniosun Journal of Engineering and Environmental Sciences (UJEES), Vol. 8 No. 2, Sept., 2026
DOI: 10.64980/ujees.v8i2.028 **Salami et al.**
Published: September 30, 2026

A SYSTEMATIC REVIEW OF RICE STRAW ASH AND PULVERISED PALM KERNEL SHELL IN LATERITIC SOIL STABILISATION

M. O. SALAMI[1*], U. A. NDATSU[2], M. A. IPAYE[3], M. T. AKINLEYE[4], L. O. SALAMI[5], and O. T. ADENIRAN[6]

[1,2,3,4]*Department of Civil Engineering, Adeleke University, Ede, Nigeria*

[5,6]*Department of Civil Engineering, Osun State University, Osogbo, Nigeria*

[*]*Corresponding Author: salami.muinat@adelekeuniversity.edu.ng*

Abstract
In tropical countries, agricultural residues present both waste-disposal challenges and opportunities for sustainable geotechnical applications. Lateritic soil, which is widely adopted for road construction, often have low strength and high plasticity and are thus in need of stabilisation. Rice Straw Ash (RSA) and Pulversihed Palm Kernel Shell (PPKS) are agricultural by-product-based materials. This study reviewed PPKS-stabilised lateritic soil with inference toward RSA's likely pozzolanic contribution. The synthesised evidence shows that the major contribution of RSA is physical reinforcement of the soil by pozzolanic reactions, resulting in improved strength characteristics, especially after curing and the contribution of PPKS is through physical reinforcement, resulting in the decreased Maximum Dry Density (MDD) and increased Optimum Moisture Content (OMC). The PPKS may contribute primarily through granular reinforcement and increased interparticle friction, whereas RSA may contribute through pozzolanic reactions and cementitious bonding. However, the amount of improvement, is very sensitive to the additive proportions, soil type and curing conditions. The results of this review support the potential of these two stabilisers as complementary stabilisers for low load applications but require further research with standardised testing protocols, testing at field scale under variable climates and evaluating life-cycle environmental impacts to build confidence in the design criteria.

Keywords
Agricultural wastes, Lateritic Soils, Pulverised Palm Kernel Shell, Rice Straw Ash, Soil Improvement

1. INTRODUCTION

Lateritic soil is widely available and essential construction materials in many tropical and subtropical parts of the world [1-4]. It is formed under the influence of humid and warm climatic conditions are highly chemically weathered and the resulting soils are a basis for many civil engineering structures such as road pavement, embankment, building foundation and earth dams [5]. The extensive use of lateritic soil is mostly due to their local availability. The engineering properties, on the other hand, of lateritic soils are very complex and variable [6, 7]. This variability is explained by the complex combination of their parent rock mineralogy and their different degree of laterization as well as environmental conditions of their formation [8]. This means that some laterite deposits have satisfactory geotechnical characteristics for construction while others are discovered to be poor in some of the performance characteristics. Lateritic soils have a high percentage of fine particles and clay minerals and are highly plastic, especially in the lateritic soils of the tropics [9]. These inherent characteristics often result in low shear strength, low workability and high sensitivity to volume changes with wetting and drying, which are not suitable for load-bearing engineering applications unless improved [10].

The most important performance criterion for any soil to be used in construction is its ability to achieve adequate mechanical strength and volumetric stability. However, lateritic soils in their natural state are not of sufficient strength for the minimum requirements in standard road and building code for subgrade and foundation soil [11]. This is a result of low bearing capacity, high plasticity, poor drainage, and excessive moisture sensitivity, making them unable to meet the required strength and stability criteria. The California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) test values of untreated lateritic soils are commonly less than the values desired for pavement layers and structural fills [6]. This poor performance is a big challenge for engineers and contractors in tropical developing countries where lateritic soils constitute the main and sometimes the only locally economical construction material [10]. Historically, soil deficiencies have been overcome through mechanical or chemical stabilisation techniques [12]. Mechanical stabilisation

is a method which involves mixing of the unsuitable soil with a granular material to enhance the gradation of the soil. However, chemical stabilisation which entails addition of additives like cement, lime or fly ash to modify the physicochemical properties of the soil, has been employed more widely because of its effectiveness in reducing plasticity and dramatically increasing strength [12].

Chemical stabilisation, come with well-known environmental and economic drawbacks [13]. Cement manufacturing is extremely energy intensive process accounting for significant percentage of anthropogenic CO_2 emissions in the world [14]. As the construction sector strives to move towards sustainability and a greener environment, this carbon footprint is becoming more significant. In addition, many small-scale infrastructure projects in developing countries may have limited economic resources and the price of cement and lime can be too expensive. The environmental impact of conventional stabilisers and the economic strain they can impose on construction budgets have generated a great need for identification and validation of alternatives, which are less expensive and environmentally friendly. With this research need, the geotechnical community is increasingly focusing on valorization of locally available by-products from agricultural and industrial activities as soil stabilizers [15].

In tropical agricultural economies, agricultural processing on large scale creates large amount of agricultural waste materials, which are usually disposed off by open burning or landfill disposal, thereby polluting the environment. Rice Straw Ash (RSA) and Pulverised Palm Kernel Shell (PPKS) are two waste streams which have received special attention for their potential use in geotechnical applications. In tropical and subtropical Asia and Africa rice is a major food crop and rice straw is produced in large amounts [16]. The resulting RSA from this combustion for energy recovery or for disposal, is a material containing a large percentage of amorphous silica, which is also present in the cement hydration process and is known to be involved in pozzolanic reactions similar to those in cement [17]. At the same time, the palm oil industry, which is a major economic activity in countries such as Malaysia, Indonesia and Nigeria, produces Palm Kernel Shells (PKS) as by-products during the production of palm oil [18]. The shells are hard, durable, and have a high friction angle and are potential mechanical reinforcement when milled into fine particles (PPKS) [19].

The use of RSA pozzolanic binder and PPKS which is a granular reinforcement are promising individually, research on their synergistic applications to the stabilisation of lateritic soil is sparse. The current literature comprises of individual experimental investigation which uses a variety of material combinations, manufacturing processes, curing schedules and performance testing procedures. One major research gap that must be addressed before these materials can be successfully implemented is the need for a systematic review of the empirical evidence in order to arrive at a comprehensive synthesis. There is the need to investigate the non-existence of the previous studies on the effects of combination of RSA and PPKS on the properties of lateritic soil.

The main contribution of this study is the first systematic, rigorous and evidence-based synthesis of the state of the knowledge on the performance of the lateritic soil stabilised with both RSA and PPKS. The results will be relevant to the general geotechnical engineer who is looking for sustainable stabilisation alternatives, as well as to policy makers with an interest in waste valorization in the construction industry. The rest of this paper is organized into a description of the highly methodological process of the systematic literature search and evidence synthesis, presentation of the results of this synthesis, which include a general overview of the literature, a deep dive into the mechanical performance data, and an identification of key methodological gaps, and discussion of implications for research and practice, followed by the results of the summary of the principal insights and recommendations.

2. SOIL ENHANCEMENT WITH PAM KERNEL SHELL

Table 1 shows the key features of the related study. The data recovered from the study comprised study identification, soil classification, type of stabilizer, content of stabiliser, cement additive, compaction test results, unconfined compressive strength, and CBR. The studies included differ in soil classification, type of stabilisers, performance measurement, such as UCS, CBR, Atterberg limits, etc. This should be taken into account when interpreting results of the review and when evaluating possible sources of between-study variability in the evidence base. In general, the characteristics table should give the reader a summary of the studies included.

2.1 Effect of Stabiliser on Mechanical Strength

The key to any soil stabilisation effort is the evaluation of mechanical strength, with the goal being to make the soil able to support loads. This subsection discusses in detail the mechanical characteristics of the soil, which are provided in the included study by [2] and which include UCS, CBR and compaction characteristics. The study, described by [2], presents a set of data that highlights the potential of milled PKS as a physical reinforcement agent as it relates to the unconfined compressive strength, a direct measure of the soil's capacity to resist axial loads without applying lateral confining pressure. The results show that the incorporation of Pulverised Palm Kernel Shell (PPKS) in the lateritic soil (without cement) led to measurable gains in strength.

Table 1: Characteristics of Related Studies

Study	Soil Classification	Stabilizer Type	Stabilizer Content	Cement Additive	Soil classification	Soil classification	Soil classification	Soil classification
[20]	A-6 (AASHTO classification)	Pulverized Palm Kernel Shell (PPKS)	varying percentages (up to 8% PPKS)	3% Ordinary Portland Cement (OPC)	Optimum Moisture Content (OMC) increased from 16% to 19.5%; Maximum Dry Density (MDD) decreased from 1.669 g/cm^3 to 0.915 g/cm^3 (decrease of 45.18%)	Peak UCS values for lateritic soil + PPKS: uncured 85.03, 7 days 96.46, 14 days 100.44	Unsoaked CBR decreased from 68.60% to 61.20% (decrease of 10.79%); Soaked CBR increased from 51.70% to 69.75% (increase of 286.4%)	Liquid limit (LL) and plasticity index (PI) decreased steadily with increase in PPKS; plastic limit (PL) increased up to 4% PPKS.

The highest values of UCS obtained were 85.03, 96.46 and 100.44 for uncured, 7 days cured and 14 days cured respectively. The progressive strengthening with the increased curing time is an important observation. It proposes that, in addition to the mechanical interlocking that occurs at a single point in the construction, the soil-stabilizer matrix may undergo a time-dependent maturing process, such as slow hydration reactions in the fine's component of the soil, or a redistribution of internal stresses. It is important to interpret such values in the context of the entire experimental matrix of the study. The use of 3% Ordinary Portland Cement (OPC) combined with the PKS led to a hybrid stabilisation system which would likely have led to better absolute strength values, but the actual UCS values for the cement-stabilised combinations are not explicitly stated for comparison. However, the results clearly show that, even if its pozzolanic activity is not as significant as its physical interlocking, PPKS is able to play a role in the composite's mechanical strength and can be considered a reinforcement material.

Perhaps the most commonly used index for pavement subgrade design is the California Bearing Ratio (CBR) test. The results of CBR from [20], show a complex and highly interesting answer to the support of PPKS. The CBR for unsoaked condition reduced from 68.60 to 61.20% with a decrease of 10.79% due to the addition of PPKS, which means there was a slight decrease in the shear strength of the material in the initial stage of application. This is probably due to the nature of the hard PPKS particles interfering with the ideal packing and continuity of the soil matrix, thereby allowing stress to be concentrated on the particles which slightly lowers the initial resistance to penetration. The soaked CBR test determines the strength of a material after it is soaked in water for a specified period of time, representing the worst-case field moisture condition, a far more dramatic and positive finding was observed. After being soaked, the CBR value of the sample was stabilised with PPKS, thereby increasing the value to 69.75% as compared to its very low value of 18.05%. This transformative improvement is the most important outcome of the whole study, because it represents the greatest weakness of many lateritic soils, a sudden drop in strength when wetted. This observation may be as a result of the PPKS particles altering the soil structure as a drainage/reinforcement network. The rigid, impervious shells retain the internal frictional and shear properties when the soil matrix around them is saturated and has no apparent cohesion. This means that PPKS could actually have a slightly adverse effect on the dry strength, but its effect on wet strength is outstanding, and is an excellent solution for enhancing the durability and service life of pavements in seasonally wet climates.

Lastly, the compaction properties are critical in determining the quality of the field construction. The compaction behaviour of the lateritic soil was demonstrated to be greatly affected by the addition of PPKS. The OMC was found to be gradually rising from 16 to 19.5% when PPKS was added. On the other hand, MDD suffered a significant decrease of 45.18% from 1.669 to 0.915 g/cm³. Both trends are physiochemically coherent and are characteristic of soils which are bound with light weight, porous or irregularly shaped additives. This rise in OMC is attributable to the higher water requirement of the PPKS particles as well as the greater void spaces created in the soil-stabilizer matrix which also requires more water for compaction to be optimally lubricated. This significant MDD reduction is due to the lower specific gravity of the organic PPKS material than the mineral soil particles. If there is a relatively large amount of the heavy soil replaced by lighter PPKS, the mass per unit volume of the compacted material should be reduced. The subtle message

of this discovery is that the presence of PKS results in a lighter weight fill material and thus decreases the dead load on the underlying subgrades, a desirable property in construction on soft ground. The lower densities and higher OMC's, also mean that moisture control in the field will require a different approach and may require more compaction effort to achieve the desired degree of compaction.

Table 2. Previous Studies on the Effect of Rice Straw Ash on Lateritic Soil

Study	PPKS Content	Cement addition	Soil classification	Soil classification	Soil classification	Soil classification	Soil classification	Soil classification	Soil classification
[20]	Varying (up to 8%)	3% Ordinary Portland Cement (OPC)	85.03 / 96.46 / 100.44 (Soil + PPKS only)	69.75 (with PPKS)	+74.12%	61.20 (with PPKS)	-10.79%	Increased from 16% to 19.5%	Decreased from 1.669 to 0.915 (-45.18%)

In Table 2, the data obtained from synthesis reflects the main results of the evaluation of mechanical strength. It is observed that the mechanical properties of the stabilised soil is a result of two competing processes: reinforcement effect of PPKS that increases the shear resistance, especially under saturated conditions and the reduction of the matrix density that reduces the overall mass per unit volume of the soil. The net effect of these is favorable for road building purposes. The drastic improvement of soaked CBR from low initial value (18.05%) to a highly serviceable value (69.75%) is the most convincing evidence of using PKS as soil stabiliser in soils of lateritic origin. This improvement is directly aimed at the main failure mode in these soils, which is when they get wet, and indicates that PKS can be used to make pavements more climate resistant. The downside of the reduced unsoaked CBR and MDD is that they are numerically less pronounced than the good qualities of wet strength and reduction in density. The data confirms that PPKS is one of the most effective materials that can be used to enhance the wet strength and workability of lateritic soil provided that the material effects are mostly physical and not chemical cementation.

Many of the stabilisation projects aim at altering the Atterberg limits, which represent critical moisture contents for the soil's behaviour. These limits have been systematically identified by [7, 20], as a function of PKS content in the form of PPKS. The results indicate a consistent and desirable trend of enhancement of plastic properties of soil. For both the Liquid Limit (LL) and the Plasticity Index (PI), the content of PPKS showed a continuous decrease without showing any discontinuities. This decrease in PI is one of the most important indicators of better soil quality, since generally, a lower PI value indicates a lower potential for swelling and shrinkage, a lower compressibility, and better workability during construction. This improvement may be linked to the dilution of the clay fraction by the non-plastic particles containing PPKS. Shell fragments are less plastic than the clay matrix and substituting them for a part of the clay body reduces the plasticity of the composite product, which in turn decreases the harmful volume changes that can occur with moisture changes. This was in keeping with the main finding of the study, where PKS is seen as a 'physical reinforcement' and 'inert filler' that mechanically restricts the swelling of the clay component.

The initial increase in Plastic Limit (PL) with PKS content reached a maximum value at about 4% before declining as more PPKS was added. There is a competition between the attraction of water by the PKS particles and breaking of the internal structure of the soil, which can be rationalized. However, PPKS particles can absorb some of the mixing water, which decreases the amount of free water for lubrication of soil particles and increases the moisture content for the soil to go from a semi-solid to plastic state. At higher concentrations, however, the PKS particles start to overpower the matrix, resulting in a more granular and less cohesive structure with a higher clay content, where the PL is more affected by the particle-to-particle friction than by the cohesion of the clay itself. There was also a peak in the Shrinkage Limit (SL) with the maximum occurring at 8% PPKS addition, followed by a decrease. This increase in SL is another very desirable effect which means that the soil shrinks less on drying, which is what it does. The higher the shrinkage limit, the more water the soil can absorb before shrinking, which will decrease the chances of cracking in dry conditions. The peak at 8% implies an optimum value at which the positive reinforcement of the PPKS network is at a maximum.

The collation of these sundry results is given in Table 3 and seems to indicate that the stabilizer is effective in attacking the most troublesome aspects of the behaviour of lateritic soils. This is further supported by the rise in SL that are in favour of the benefit as it shows lower potential of desiccation cracking. The overall reduction in plasticity was not negated by the trend in the plastic limit, which was more complex. The peak at 4% PPKS is interpreted as being the optimum dosage to maximize water-holding capacity of the soil-plastic fraction. This is followed by a decline towards a more granular and friction-dominated material at higher concentrations of shells.

Table 3. Previous Studies on the Effect of Combination of PPKS and RSA on Lateritic Soil

Study	Soil Type	Stabilizer	Liquid Limit (LL)	Plasticity Index (PI)	Plastic limit (PL)	Shrinkage Limit (SL)
[20]	A-6 Laterite	Pulverized Palm Kernel Shell (PPKS)	Decreased with increasing PPKS content	Decreased with increasing PPKS content	Increased up to 4% PPKS, then decreased	Increased up to 8% PPKS, then decreased

The various improvements in plasticity, coupled with the dramatic boost in soaked CBR, indicate that PPKS is not only a strength additive but a complete stabiliser that upgrades on various important performance parameters of the lateritic soil. The overall results are a material that is less plastic, less shrinkable, and much more resistant to loss of strength after wetting than the untreated soil. This type of improvement is typical of an effective stabilisation system that is achieved by physical reinforcement as well as dilution of the problematic clay fraction to produce a composite material with an improved engineering property for the application of road construction and similar low load applications.

3. SUMMARY OF RELATED STUDIES

The discussion below is limited to the mechanism of action of a broadly similar granular material since the study identified only PPKS with cement as an additive, and did not involve the incorporation of RSA which would add a different pozzolanic chemistry to the composite system. However, the results from [10, 12, 13, 15 - 19], give a good foundation to understanding what might be expected of a dual stabilisation system and how they might complement one another as well as the outcomes of the geotechnical stabilisation literature.

When all the included studies are combined, it indicates a dual mechanistic pathway for lateritic soil stabilisation using a rigid granular filler such as PPKS and a pozzolanic binder like RSA, which was not directly tested. The PPKS, which is mainly used as reinforcement agent, increases the internal friction of the mixture and serves as a strong internal skeleton structure that retains the shear strength even in saturated condition [22]. This is a robust and meaningful finding, as evidenced by the dramatic 74.12% increase in soaked California bearing ratio. The decreases in plasticity index and increments in shrinkage limit, as reported by [18] also confirm the ability of the granular filler to restrain the volume changes of the clay fraction. The pozzolanic activity of the RSA would be expected to provide cementitious bonds which should further increase the unconfined compressive strength of the resultant composite and decrease its long-term plasticity due to chemical alteration to the clay minerals as indicated in the previously mentioned studies on the pozzolanic activity of rice husk ash and similar siliceous ashes [17]. The umbrella effect is that a binary stabilisation system might yield a composite that would combine the short-term wet strength and volume stability properties and characteristics of the granular filler with the longer-term chemical strength of the pozzolanic ash. The synergy is a new approach to the conceptual understanding of sustainable soil stabilisation in tropical environment.

These results have both forward and specific implications for geotechnical practice. The most actionable takeaway for pavement engineers in tropical areas is the potential to develop a resilient subgrade or subbase layer that does not lose much strength when subjected to prolonged wetness properties that were identified as the greatest transformative result of the PPKS stabilisation [10, 12, 13, 15 - 19, 22 - 24]. For this purpose, it is recommended that the use of PPKS should be considered as a major stabilizer for lateritic soils, while knowing that the material will lower the maximum dry density of the soil and alter the optimum moisture content which can be controlled by specifying a specific compaction. Also, the pozzolanic RSA could then be specifically selected for applications where a greater long-term unconfined compressive strength is desired such as in the upper layers of a pavement structure. The use of locally sourced agricultural wastes such as palm kernel shells and rice straw ash for valorization serves as a practical alternative to Portland cement, which is more expensive and environmentally harsh, and is in line with the overall goal of building sustainability in developing countries [7, 15]. The lower weight of the PPKS-stabilised material also provides an advantage for its application in construction compared to soft, compressible subgrades because the decreased dead load on the foundation reduces the potential for bearing capacity failure.

It is obvious from the current evidence base that there are clearly some areas where further research is needed. Most importantly, there is a clear requirement for a multi-centre experimental programme in a systematic manner to explore the combined effect of RSA and PPKS on a range of lateritic soils representative of the geographies found in tropical regions. These types of studies should now shift from the present single soil and single add additive study to a full factorial experimental design which investigates the effect of blended RSA and PPKS content (0, 2.5, 5, 7.5, 10, 12.5, and 15%) on the development of mechanical strength. Furthermore, scanning electron microscopy, X-ray diffraction and X-ray fluorescence

studies are required to directly observe the cementitious products that result from RSA and determine the physical interlocking and bridging mechanisms that occur between PPKS particles and in the soil matrix to provide a mechanistic basis for these observed performance trends. In addition, future studies should examine the field performance of the selected optimal blend of RSA-PPKS that were placed as trial sections in the pavement, and compare their in-situ density, strength, and deflection properties to control sections of the pavement, which were cement-stabilised and over a minimum of two years to account for seasonal moisture variations.

Lastly, a standard predictive model that correlates the laboratory determined properties of the stabilised soil, like CBR, UCS and plasticity index with the performance of an actual pavement structure under traffic loading and environmental exposure, would be extremely useful in transitioning the present experimental findings into practical and codified design guidelines for the construction of roads in the tropics.

4. CONCLUSION

This systematic review on the dual stabilisation of lateritic soil using rice straw ash and pulverised palm kernel shell. The studies examined showed that the soaked California bearing ratio increased by 70 - 74.12% with the addition of pulverized palm kernel shells as granular reinforcement and the plasticity index was always decreased. Thus, solving the major engineering problem of lateritic soils which is catastrophic loss of strength when wet. For the PPKS-dominated evidence reviewed, physical reinforcement appears to be an important stabilisation mechanism. However, the relative contributions of physical reinforcement and pozzolanic cementation in a combined RSA–PPKS system remain to be experimentally established.

Based on the findings of this study, the practical implication is that in tropical countries where lateritic soils are dominant, pulverised palm kernel shell (and of similar granular bio-wastes) is a viable low-cost option for the formation of climate resilient subgrades for pavements. The theoretical significance of this review is the identification of the possibility that the pozzolanic ash and the granular filler has not yet been demonstrated directly, through experimentation.

This is the need of the hour and future research should focus on this deficiency by having systematic factorial experiments involving different levels of rice straw ash and pulverised palm kernel shell contents combined on various lateritic soil types. These studies must feature standard durability testing, microstructural examination, and field testing to help close the gap that exists between potential in the laboratory and in the field.

REFERENCES

[1] Oyelami, C. A., and Van Rooy, J. L. (2016). A review of the use of lateritic soils in the construction/development of sustainable housing in Africa: A geological perspective. *Journal of African Earth Sciences*, *119*, 226-237. https://doi.org/10.1016/j.jafrearsci.2016.03.018

[2] Agasnalli, C., Deepak, M. S., and Reddy, C. A. (2022). Global view of lateritic soil improvement for construction purposes in tropical countries. *Materials Today: Proceedings*, *65*, 1895-1899. https://doi.org/10.1016/j.matpr.2022.05.158

[3] Rusdi, M. A., and Daud, N. N. N. (2022). Fly ash stabilised lateritic soil as subbase material: A review. *Earth Sciences Malaysia (ESMY)*, *6*(1), 15-23. http://doi.org/10.26480/esmy.01.2022.15.23

[4] Ameen I. O., Salami L. O., Adeyemo Q. A., Tijani M. A. and Bello, A. A. (2026). Effect of Compaction Energies on Geotechnical Properties of Stone Dust Stabilised Lateritic Soil. *Discover Civil Engineering.* 3, 94**.** https://doi.org/10.1007/s44290-026-00470-6

[5] Kandalai, S., John, N. J., and Patel, A. (2023). Effects of climate change on geotechnical infrastructures—state of the art. *Environmental Science and Pollution Research*, *30*(7), 16878-16904. https://doi.org/10.1007/s11356-022-24788-7

[6] Yamus, Y. B., Rashid, A. S. A., Ahmad, K., and Abd Rahman, N. (2019). A review on the fundamental engineering properties of compacted laterite soil at different gradations. *Journal of Advanced Research in Applied Sciences and Engineering Technology*, *16*(1), 10-19. https://www.akademiabaru.com/doc/ARASETV16_N1_P10_19.pdf

[7] Daramola, S. O., Hingston, E. D. C., and Demlie, M. (2024). A review of lateritic soils and their use as landfill liners. *Environmental Earth Sciences*, *83*(3), 118. https://doi.org/10.1007/s12665-023-11392-2

[8] Aboubakar, A., Kentsa, B. I. M., Tchatchoua, F. T. R., Frederic, M., Guedala, A., Ngapgue, F., and Tamo, T. T. (2025). Correlation between mineralogical, chemical and geotechnical properties of lateritic soils of Ngaoundal: implication for road construction. *Discover Soil*, *2*(1), 30. https://doi.org/10.1007/s44378-025-00056-1

[9] Onwo, E. S., Emeh, C., and Igwe, O. (2022). Effect of geochemical composition of lateritic soils on their geotechnical properties. *Indian Geotechnical Journal*, *52*(4), 877-894. https://doi.org/10.1007/s40098-022-00628-w

[10] Daraei, A., Sherwani, A. F. H., Faraj, R. H., Mohammad, S., Kurdo, S., Zare, S., and Mahmoodzadeh, A. (2019). Stabilisation of problematic soil by utilizing cementitious materials. Innovative Infrastructure Solutions, 4(1), 33. https://doi.org/10.1007/s41062-019-0220-5

[11] Amadi, A. N., Akande, W. G., Okunlola, I. A., Jimoh, M. O., and Francis, D. G. (2015). Assessment of the Geotechnical Properties of Lateritic Soils in Minna, North Central Nigeria for Road design and Construction. http://irepo.futminna.edu.ng:8080/jspui/handle/123456789/28370

[12] Elnimr, M. T., Azzam, W. R., Agrama, F. A., and Ata, M. M. (2026). Advances in Problematic Soil Stabilisation: State-of-the-Art. *ERJ. Engineering Research Journal*, *49*(2), 159-171. https://doi.org/10.21608/erjm.2025.407836.1423

[13] Bahmanpour, A., Ghahremani, M., and Fattahi, S. M. (2026). Recycling waste concrete into alkali-activated geo-binders for sand stabilisation. *Scientific Reports*. https://doi.org/10.1038/s41598-026-44832-7

[14] Andrew, R. (2018). Global emissions from cement production. *Earth System Science Data*. https://doi.org/10.5281/zenodo.831455

[15] Dauda, D., and Dominic, M. (2022). Effectiveness of agricultural wastes in soil stabilisation. *Sustainability, Agri, Food and Environmental Research*. https://doi.org/10.7770/safer-V10N1-art2452

[16] Singh, G., Gupta, M. K., Chaurasiya, S., Sharma, V. S., and Pimenov, D. Y. (2021). Rice straw burning: a review on its global prevalence and the sustainable alternatives for its effective mitigation. *Environmental Science and Pollution Research*, *28*(25), 32125-32155. https://doi.org/10.1007/s11356-021-14163-3

[17] Roselló, J., Soriano, L., Santamarina, M. P., Akasaki, J. L., Monzó, J., and Payá, J. (2017). Rice straw ash: A potential pozzolanic supplementary material for cementing systems. *Industrial Crops and Products*, *103*, 39-50. https://doi.org/10.1016/j.indcrop.2017.03.030

[18] Siagian, U. W. R., Wenten, I. G., and Khoiruddin, K. (2024). Circular economy approaches in the palm oil industry: Enhancing profitability through waste reduction and product diversification. *Journal of Engineering and Technological Sciences*, *56*(1), 25-49. https://doi.org/10.5614/j.eng.technol.sci.2024.56.1.3

[19] Jamil, M. A. B., Hayano, K., Kassa, A., Sekine, R., and Mochizuki, Y. (2024). Curing effects on geotechnical properties of clays treated with palm kernel shell ash and rice husk ash: Insights from water absorption characteristics of stabilizers. *Case Studies in Construction Materials*, *20*, e02947. https://doi.org/10.1016/j.cscm.2024.e02947

[20] Adewale, O., Segun, A., and Ariyo, A. (2017). Structural evaluation of the effect of pulverized palm kernel shell (PPKS) on cement-modified lateritic soil sample. *American Journal of Civil Engineering*, *5*, 205. https://doi.org/10.11648/j.ajce.20170504.12

[21] Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., and Moher, D. (2021). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *bmj*, *372*. https://doi.org/10.1136/bmj.n71

[22] Monrose, J., and Tota-Maharaj, K. (2018). Technological review of permeable pavement systems for applications in small island developing states. *CLEAN–Soil, Air, Water*, *46*(9), 1700168. https://doi.org/10.1002/clen.201700168

[23] Robinson, R., and Thagesen, B. (2018). *Road engineering for development*. CRC Press. https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=Robinson%2C+R.%2C+and+Thagesen%2C+B.+%282018%29.+Road+engineering+for+development.+CRC+Press.&btnG=

[24] Latif, A., Muda, M. F., Zainudin, M. R., and Dao, H. (2025). Review of Asphalt Pavement Adaptation to Climate Change: Enhancing Resilience and Sustainability. *CONSTRUCTION*, *5*(2). https://doi.org/10.15282/construction.v5i2.12670