Received: 1 January 2024 | Revised: 26 April 2024 | Accepted: 28 May 2024 | Published online: 3 June 2024

RESEARCH ARTICLE

Archives of Advanced Engineering Science
2024, Vol. 00(00) 1–7
DOI: 10.47852/bonviewAAES42022403

BON VIEW PUBLISHING

Calcium Carbide and Wood Ash as Environmentally Friendly Soil Stabilizers for Enhanced Subgrade Performance

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Abstract: This study looks at the potential of waste calcium carbide (WCC) and wood ash (WA) as soil stabilizers to improve the engineering characteristics of subgrade soil. The investigation begins by characterizing the properties of the untreated soil, indicating a liquid limit of 24.6%, linear shrinkage of 7.6%, and a non-plastic nature due to the lack of a plastic limit. In addition, the soil composition comprises a mere 2% of small particles measuring less than 63 µm, while a substantial 74% of the particles fall within the range of 63 µm to 2 mm. The particle density of untreated soil is found to be 2.86, beyond the typical soil limitations. Subsequently, an investigation was conducted to examine the impact of WCC and WA on Atterberg limits, compaction characteristics, and California bearing ratio (CBR) values. The findings indicate that the incorporation of WCC and WA leads to a reduction in the liquid limit by a maximum of 18.70% and linear shrinkage by a maximum of 55.26%. Compaction properties show an increase in optimal water content and a minor decrease in maximum dry density. Importantly, CBR values significantly improved, with the soil treated with 6% WCC and WA demonstrating a CBR value of 26.9%, exceeding the subgrade acceptability requirement in road construction. This study highlights the potential of WCC and WA as cost-effective and sustainable soil stabilizers, particularly in areas where traditional stabilizing materials are limited. More research into optimization and long-term performance can help to realize the full potential of this novel method for soil stabilization.

Keywords: soil stabilization, waste calcium carbide, wood ash, engineering properties, California bearing ratio

1. Introduction

The foundation is the backbone of any construction project, giving the required support to the whole structure. The underlying soil is an important aspect in determining the strength and durability of this foundation. In order to successfully address soil-related issues, it is important to possess a comprehensive understanding of the principal constituents that govern their behavior. The determination of a soil's load-bearing capability is reliant on several significant parameters, including shear strength [1–3], swell-shrinkage potentials [4, 5], moisture absorption [6], and particle size distributions [7, 8]. In several situations, the inherent characteristics of soils may not align with the requirements for an appropriate foundation material, hence requiring the use of soil stabilization techniques.

Soil stabilization is a procedure that involves changing one or more characteristics of soil in order to improve its engineering properties. It includes a variety of subgrade materials, ranging from expansive clays to granular soils [9]. Soil stabilization can be accomplished mechanically or chemically.

Mechanical stabilization entails the use of physical measures to increase the shear strength of the soil. This category includes techniques such as compaction, soil reinforcement, and soil nailing. Compaction, for example, involves the use of heavy machinery to reduce soil volume and enhance density and strength. Soil reinforcement, such as geotextiles and geogrids, increases tensile strength. Soil nailing is the process of inserting fiberglass nails or anchors into the soil to increase strength.

Chemical stabilization, on the other hand, uses chemical agents to change the properties of soil and increase strength and stability. Chemicals such as lime, cement, or fly ash can be added to soil to cause a chemical reaction that enhances the soil's characteristics [10–13]. When these compounds react with soil particles, they form a stronger and more stable matrix than the original soil. This study looks at the usage of waste calcium carbide and wood ash (WCC and WA) as possible subgrade soil stabilizers. Using WCC and WA for soil stabilization has various benefits for improving soil engineering qualities. Because of its tiny particle size, WCC residue may efficiently stick to soil grains when used on the surface [9, 14]. Furthermore, WA includes alumina and silica, which aid in soil particle bonding, increase textural characteristics, and improve erosion resistance [15, 16]. Moreover, the combination of materials

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decreases soil porosity, improves permeability, and increases the soil's load-bearing capacity. Considering WCC and WA are frequently accessible from waste, they can significantly lower material costs when compared to standard cementitious materials like cement or lime.

This study intends to investigate the potential of WCC and WA as soil stabilizers, providing light on their efficacy in enhancing soil engineering qualities while also considering their environmental and economic advantages.

2. Literature Review

2.1. Overview

Soil stabilization is a crucial aspect of the construction industry that intends to strengthen the characteristics of soil in order to improve its performance during construction projects. It includes a variety of methods, employing both conventional (such as cement, lime, and fly ash) and unconventional stabilizers (such sulfonated oils, asphalt, and ionic stabilizers). The primary objective is to increase the volume, stability, strength, permeability, and durability of a given material while making the most efficient use of available resources [17].

Achieving engineering goals typically entails considerations regarding current soil suitability. To achieve project needs, one must either accept the constraints of the site material, replace it with better options, or adjust its inherent characteristics. The primary considerations concentrate around guaranteeing the stability, durability, and ability to withstand unfavorable circumstances of the soil before and after construction, emphasizing the proactive function of stabilization [18].

Chemical stabilization refers to the process of using chemicals to improve the stability and properties of soil. Soil modification, on the other hand, involves altering the characteristics of soil to enhance its performance and suitability for certain applications.

Chemical stabilization is a crucial approach that utilizes additions such as lime, cement, and fly ash to modify soil properties. This approach demonstrates cost-effectiveness, environmental friendliness, and efficiency, especially when making use of resources that are readily accessible in the local area. Chemical stabilization refers to the process of combining chemicals with particular moisture content to improve the characteristics of soil in various engineering projects [19].

2.2. Challenges in engineering with soft soils

Soft soils present considerable obstacles in building due to their poor strength, excessive compressibility, and vulnerability to moisture. Chemical stabilization is a promising method that involves changing the properties of soil by adding substances like lime and cement. It is important to note that soil modification refers to altering the basic characteristics of the soil, while soil stabilization focuses on improving its texture, strength, and CBR value. This makes chemical stabilization a suitable option for ensuring the long-term viability of construction projects [20].

2.3. Review of existing literature

The following section presents a compilation of different investigations on methods for enhancing soil stability. It highlights the utilization of various stabilizers and soil types, as well as the execution of tests and the resulting significant discoveries. Each study investigates numerous stabilizers and their effects on soil behavior, providing insights on how to improve soil strength, stability, and durability in diverse engineering applications.

The studies conducted by Matthew and Godwin [21] and Razvi et al. [22] focus on the use of lime and bitumen emulsion-cement mixtures, respectively, to improve soil stability. These studies employ different testing methods to investigate this enhancement. The studies conducted by Abdila et al. [23] investigate the use of non-traditional stabilizers such as pine needles and nanoparticles. These studies provide insights into the intricate effects of these stabilizers on soil behavior and features.

Krishana and Pavan [19] and Oluwatuyi et al. [12] and other recent research have investigated the use of lime-fly ash combinations, epoxy resin, calcium chloride dehydrate, and WCC with WA as materials for waste management. Together, they highlight the capacity of various materials to modify soil characteristics, with a focus on their advantages, disadvantages, and economic consequences.

3. Materials and Methods

3.1. Sample soil

Soil samples were obtained from the area behind the male hostels at Hassan Usman Katsina Polytechnic in Katsina to guarantee minimum soil moisture loss. To accurately reflect the subgrade soil, the samples were taken one meter below the surface of the ground.

3.2. Waste calcium carbide

WCC, a solid byproduct of the manufacturing of acetylene gas, was obtained from a local welder at the Mashi Bus Station in the Mashi Local Government Area of Katsina State, Nigeria. Prior to its use, the WCC underwent a process of air-drying, followed by grinding into a fine powder using a mortar and pestle. Ultimately, a 300-micron sieve was employed to facilitate the segregation of the particles. According to Jaturapitakkul and Roongreung [24], WCC is known to include cementitious elements such as silica, alumina, and calcium oxides (CaO).

3.3. Wood ash

WA is the fine powder left behind following the burning of wood, which is commonly produced in wood stoves, fires, or industrial power plants [25, 26]. The building site next to the College of Engineering at Hassan Usman Katsina Polytechnic, in Katsina, provided the WA used in this study. It was first obtained as ash from burned wood.

Table 1 shows the chemical composition of WCC and WA, as well as certain physical parameters. Understanding the properties and possible uses of these waste products in a variety of industries—particularly construction and environmental management—is made possible by these studies.

Starting with the composition of WCC, it is clear that it comprises a considerable quantity of CaO, accounting for around 97.8%. Because of the high CaO content, WCC may be used as a raw material to make cementitious products or as an important supply of calcium for industrial operations. WCC also includes trace quantities of other chemicals such as aluminium oxide (Al_2O_3), iron (III) oxide, magnesium oxide, and silicon oxide, however at low concentrations.

On the other hand, the chemical profile of WA is distinct. While WA includes CaO, albeit at a lesser percentage than WCC, it has

Table 1
Chemical composition of waste calcium carbide and wood ash

Chemical Compound		Composition of waste calcium carbide (WCC) (%)				Composition of wood ash (WA) (%)	
Aluminium oxide	Al_2O_3	1.3	3.62	0.46	2.00	28.0	17.1
Calcium oxide	CaO	97.8	90.1	74.0	56.41	10.53	3.5
Iron (III) oxide	Fe_2O_3	0.50	1.2	3.1	1.87	2.34	9.8
Magnesium oxide	MgO	0.18	–	–	0.70	9.32	0.7
Potassium oxide	K_2O	–	–	–	0.10	2.34	9.8
Silicon oxide	SiO_2	0.07	–	–	6.49	9.32	0.7
Sulfur trioxide	SiO_3	–	–	–	0.36	–	–
Sodium oxide	Na_2O	–	–	–	0.18	2.34	9.8
Specific gravity	–	–	–	–	2.26	2.13	–
Blaine fineness (cm^2/g) n.o.	–	–	–	–	4100		–
Bulk density (kg/m^3)	–	–	–	–	–	760	–
LOI	–	–	–	–	31.74	27	31.6
Reference		(Ajala et al. [27])	(Latifi et al. [28])	(Saldanha et al. [29])	(Krammart and Tangtermsirikul [30])	(Abdullahi [25])	(Siddique [31])

greater quantities of Al_2O_3 and considerable amounts of silicon oxide. The compositional variations between WCC and WA point to different sources and processing techniques; WA is most likely the result of wood combustion and contains residue from silica-rich materials.

The physical attributes included in the table, such as specific gravity, Blaine fineness, bulk density, and loss on ignition, provide more information on these waste materials. For example, specific gravity readings indicate WA's relative density to water, which might advise handling and processing factors. The Blaine fineness values indicate the particle size distribution and surface area of WA, which can affect its reactivity in a variety of applications, including pozzolanic reactions in cementitious systems. Furthermore, bulk density values provide insight into packaging and storage problems for these materials, especially in large-scale industrial settings.

3.4. Laboratory tests

The untreated soil sample was subjected to a number of tests in a laboratory to evaluate its engineering properties. The soil sample was subjected to Atterberg limit testing, which included finding out the liquid limit, plastic limit, and linear shrinkage. These tests were carried out in compliance with British Standard (BS) procedures [32].

Particle distribution and particle density test: British standard procedures were used to determine the particle distribution [33] and particle density of the soil [34].

Compaction test: In accordance with BS guidelines [35], a soil compaction test was performed. California bearing ratio (CBR) test: In accordance with BS:1377-4 [36], the CBR test was carried out.

3.5. Stabilization of soils

The untreated soil sample was stabilized using different concentrations (2%, 4%, 6%, and 8%) of the stabilizing material, which was a mixture of WCC and WA in a 1:1 ratio. On the stabilized soil, the following tests were carried out, once again according to BS standards:

Atterberg limits: The Atterberg limit tests were repeated on the stabilized soil samples.

Compaction test: The stabilized soil underwent a compaction test.

CBR test: The stabilized soil samples were also subjected to the CBR test.

All the test specimens were conducted immediately after mixing the soil with the stabilizer.

4. Result and Discussion

4.1. The untreated soil's characteristics

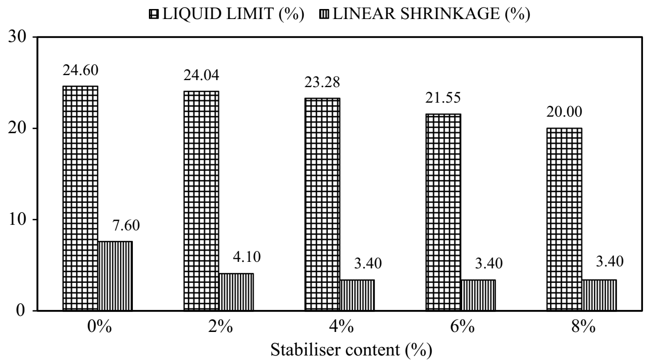
Table 2 displays the findings of laboratory testing used to characterize the properties of the untreated soil. Analysis of soil provides essential insights into its characteristics, elucidating its behavior under varying conditions. The liquid limit of the soil, measured at 24.6%, indicates the moisture level at which it changes from a solid to a liquid condition, revealing its susceptibility to changes in moisture. The absence of a plastic limit indicates that the soil does not possess plastic properties, meaning it does not exhibit the usual capacity to be molded when wet and become brittle when dry. The soil's linear shrinkage of 7.6% highlights its inclination to decrease in volume when it dries, which is vital for evaluating its stability and sensitivity to settlement.

Evaluating the distribution of particle sizes is crucial: 74% of the soil is able to pass through a 2mm sieve, whereas only 52% and a mere 2% are able to pass through the 425μm and 63μm sieves, respectively. The distribution of particles in the soil provides indications about its composition and how it behaves when subjected to a load. This observation is further supported by Keller and Dexter [37] and Hasan et al. [38], who attribute the low concentration of small particles to the soil's characteristics of having a low liquid limit, linear shrinkage, and non-plasticity.

Table 2
Properties of the untreated soil

Properties	Result
Liquid limit	24.6 %
Plastic limit	Non-plastic
Linear shrinkage	7.6 %
Particles density	2.86
Passed 2mm	74%
Passed 425μm	52%
Passed 63μm	2%
Maximum dry density	1.86Mg/m^3
Optimum water content	9.4%
CBR	3%

Figure 1
The Atterberg limits result of natural and stabilized soil



The measured particle density of 2.86 provides important information on the composition and compactness of the soil; however, it falls outside the average range for soil samples, which is typically between 2.60 and 2.75. Hao et al. [39] suggest that the divergence observed might indicate the existence of dense minerals such as magnetite, zircon, tourmaline, and hornblende in the soil, which affects its density.

Moreover, the findings indicate the compaction properties of the soil, revealing a maximum dry density (MDD) of 1.86 Mg/m³ and an optimal water content (OWC) of 9.4%. These variables are crucial in construction as they indicate the soil's capacity to achieve maximum density and optimal moisture levels for compaction. The high MDD and low OWC values were caused by the low percentage (2%) of fine particles in the soil [14, 16]. Nevertheless, the soil's CBR value of 3%, which is likely attributed to the considerable amount of loose sand, indicates a requirement for major enhancement in order to adequately sustain structures or highways [40]. To improve the soil's engineering characteristics for construction, it is necessary to implement compaction procedures or stabilization techniques.

4.2. Impact of WA and WCC on Atterberg limits of the soil

Figure 1 illustrates the impact of WCC and WA on the Atterberg limits of soil. As the proportions of WCC and WA increased, both the soil's linear shrinkage and liquid limit decreased. Specifically, with the addition of 8% WCC and WA, the liquid limit decreased by 18.70% and linear shrinkage by 55.26%, representing the most significant reduction observed. The addition of WCC and WA led to a notable decrease in both liquid limit and linear shrinkage, with the most substantial effect observed at an 8% addition of WCC and WA. The objective is to ascertain the fixation point of WCC and WC, which is the point where changes in Atterberg limits become insignificant and is designated as the fixation point [41]. At this juncture, all the natural pozzolanic materials in the soil have been utilized by CaO present in the WCC and WA.

These findings are in line with earlier research by Sani et al. [42] and Guttikonda and Abhilash [18], which all noted a decrease in liquid limit once stabilizing chemicals were added. The improved soil properties brought on by stabilization can be linked to the reduction in liquid limit. Conversely, Pakbaz and Alipour [43] report an increase in the liquid limit and plastic limit of cement-treated Iranian clay. Chew et al. [44] linked the increase in the liquid limit of the soil to the microporous characteristics of the material's aggregated particles, which confine water within intra-aggregate pores.

4.3. Impact of WA and WCC on soil compaction properties

The results of compaction tests on soil treated with various concentrations of WCC and WA ranging from 0% to 8% are shown in Figure 2. The OWC of the soil rose as WCC and WA were applied, with a 6% WCC and WA addition producing the largest increase. The lowest reduction in MDD occurred at 6% calcium carbide and WA concentration, where the MDD reduced by 4% in comparison to the untreated soil.

Upon comparing the findings shown in Figure 2 with the results obtained by other researchers, as shown in Table 3. The findings of our experiment are not consistent with the trends in prior studies on the effect of stabilizers on soil properties. For example, Suresh et al. [45] observed a different trend to ours when Bentonite clay was treated with WA. They specifically highlighted that untreated soil had the greatest MDD value, which was 1.135 g/cc. Furthermore, their findings showed a modest decrease in MDD, reaching 0.951 g/cc at a 10% WA dose. As the concentration of WA rose, MDD increased, peaking at 1.039 g/cc for a 20% dose and then dropping for 30% and 40% dosages.

Moreover, Bhardwaj [9] found that treating soil with differing quantities of gypsum had different results. In their investigation,

Figure 2
The result of Compaction characteristic with different percentages

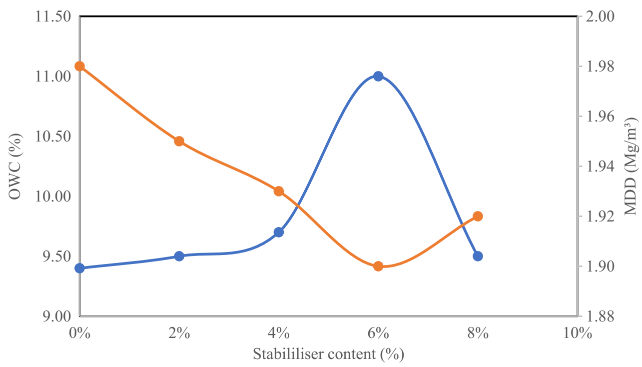


Table 3
Comparison of compaction characteristic of soils from previous researchers

References	Stabilizer used	Change in MDD (%)	Change in OWC (%)
Bhardwaj [9]	4% Gypsum + 1% $Cacl_2$	+7.43	−37.57
Suresh et al. [45]	Wood ash	−16.21	+27.66
Current research	4% Calcium carbide and wood ash	−4.04	+17.02

MDD increased by 7.43%, but OWC reduced by 37.57% after adding 4% gypsum. These mismatches highlight the complex impacts that various stabilizers may have on soil properties, emphasizing the need to take individual stabilizer-soil interactions into account in engineering applications.

The utilization of WCC and WA as stabilizers in the current studies caused a decrease in MDD by 4% and an increase in OWC by 17%. A possible reason for the reduced MDD might be the cation exchange mechanisms triggered by the Ca^{2+} ions found in WCC and WA. These actions probably helped the soil particles clump together and form larger aggregates, resulting in a reduction in the ratio of weight to volume and an increase in empty spaces between the particles in the soil structure. Hence, this change in the configuration of particles may have had a role in the reported decrease in MDD [45].

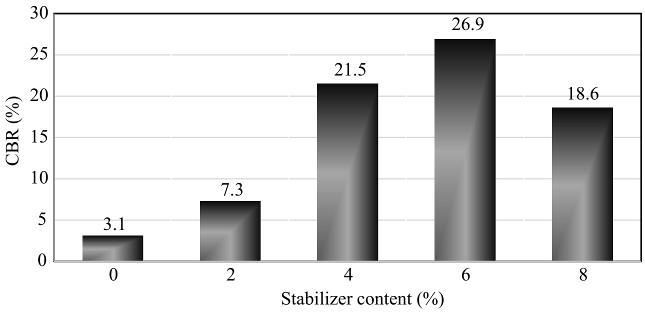
The disparity in specific gravities among WCC, WA, and the soil may also have a role. Due to their lower specific gravities, the addition of WCC and WA in the soil-stabilizer mix may have affected the total weight per unit volume of the blend, which might have contributed to the observed drop in MDD.

To summarize, our research findings contradict the established pattern of prior investigations, which have demonstrated an association between the addition of stabilizers and an increase in MDD and a decrease in OWC. The unanticipated decrease in MDD and rise in OWC subsequent to the inclusion of WCC and WA as stabilizers highlights the necessity for more investigation to clarify the complex mechanisms that regulate these changes in soil characteristics.

4.4. The impact of WA and WCC on soil CBR

Figure 3 shows the results of CBR tests performed on soil samples treated with varied amounts of WCC and WA. Notably, incorporating WCC and WA into the soil significantly increases CBR values. While the untreated soil had a low CBR value of 3.1%, the soil treated with 6% WA and calcium carbide had a significantly higher CBR value of 26.9%. This significant rise in CBR values in treated soil samples implies that WCC and WA

Figure 3
Effect of waste calcium carbide and wood ash on CBR of the soil



have a good influence, which might be ascribed to their physical characteristics or function as fillers, increasing compressive strength [46].

Supporting this hypothesis, Sefene [47] discovered that adding WA within a particular threshold increases soil strength; but, above this threshold, the strength of the stabilized soil decreases due to aggregation. As the radius of WCC and WA particles surrounding the soil particle increases, binding strength decreases. Furthermore, increasing levels of WCC and WA content result in an excess of CaO, which causes soil expansion and disintegration, resulting in decreased structural integrity [46]. This concept is supported by earlier research undertaken by Butt et al. [48] and Suresh et al. [45].

The findings given herein are congruent with previous studies by Bhardwaj [9], Nyemb Bayamack et al. [49], Singh et al. [50], and Suresh et al. [45] reinforcing the current understanding of the area.

IRC:37 Guidelines for the Design of Flexible Pavement [51] state that roads capable of supporting 450 or more commercial vehicles per day should have subgrade CBR values greater than 5%. Since the CBR values in this investigation were more than 5%, it can be derived that the soil treated with 6% WCC and WA is appropriate for use as a subgrade material for constructing pavements.

5. Conclusion

This study investigated the efficacy of WCC and WA as soil stabilizers in improving the mechanical properties of subgrade soil. Several major results developed as a result of extensive research, changing understanding and leading to insightful conclusions.

Initially, the intrinsic features of untreated soil were investigated, which revealed a liquid limit of 24.6%, a linear shrinkage of 7.6%, and a non-plastic nature with no obvious plastic limit. Particle size distribution study revealed a high concentration of particles ranging from 63μm to 2mm, with only 2% of fine particles smaller than 63μm. Notably, the particle density of 2.86 exceeded the typical soil sample values.

The study additionally examined WCC and WA's effect on Atterberg limits, revealing a significant reduction in both liquid limit and linear shrinkage after their addition to the soil. The greatest significant decrease was reported when 8% WCC and WA were combined, consistent with previous research indicating improved soil properties after stabilization.

Furthermore, the incorporation of WCC and WA impacted soil compaction characteristics. As stabilizer content increased, so did the OWC, with the greatest rise occurring at 6% WCC and WA concentration. Conversely, the MDD decreased, albeit to a smaller amount, especially at 6% calcium carbide and WA content.

CBR studies revealed a considerable increase in CBR values after the introduction of WCC and WA into the soil. Notably, soil treated with 6% WCC and WA had a great CBR value of 26.9%, which exceeded the required threshold for subgrade material in road construction.

In conclusion, the use of WCC and WA as soil stabilizers represents a viable route for improving subgrade soil characteristics, providing a cost-effective and sustainable option that is especially relevant for building projects in resource-constrained locations. Future studies might focus on optimization ways and the long-term performance effects of such stabilization solutions.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Author Contribution Statement

Samaila Saleh: Conceptualization, Methodology, Formal analysis, Resources, Data curation, Writing – review & editing, Visualization, Supervision, Project administration. **Idris Surajo:** Conceptualization, Methodology, Formal analysis, Investigation, Resources, Writing – original draft, Project administration. **Muhammad Surajo:** Formal analysis, Investigation, Resources, Writing – original draft, Project administration. **Abubakar Tsagem Idris:** Formal analysis, Investigation, Resources, Writing – original draft, Project administration. **Abdullahi Umar:** Formal analysis, Investigation, Resources, Writing – original draft, Project administration.

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How to Cite: Saleh, S., Surajo, I., Surajo, M., Tsagem Idris, A., & Umar, A. (2024). Calcium Carbide and Wood Ash as Environmentally Friendly Soil Stabilizers for Enhanced Subgrade Performance. *Archives of Advanced Engineering Science*. https://doi.org/10.47852/bonviewAAES42022403