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Original Article

Soil Stabilization Using Eco-Friendly Additives

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ABSTRACT

Soil stabilization is an important geotechnical process used to improve weak or problematic soils for construction purposes. Traditional methods rely on additives like cement, lime, and bitumen, which, despite their effectiveness, contribute to high energy consumption, greenhouse gas emissions, and environmental degradation. In response, eco-friendly soil stabilization techniques have gained attention. These methods use sustainable materials such as industrial by-products (fly ash, GGBS), agricultural wastes (rice husk ash, bagasse ash), natural fibers (coir, jute), biopolymers, and microbial agents (MICP). These additives enhance soil strength, durability, and resistance through mechanisms like pozzolanic reactions, reinforcement, bio-cementation, and microstructural improvement. The study reviews classifications of these materials, stabilization methods, testing procedures, and performance evaluation. Compared to conventional methods, eco-friendly approaches show significant improvements in strength, CBR, durability, and moisture resistance, while also promoting waste utilization and environmental sustainability. Overall, green soil stabilization offers a cost-effective, sustainable, and technically viable solution for modern geotechnical applications, particularly in pavements, embankments, and low-volume roads.

KEYWORDS

Soil Stabilization, Eco-Friendly Additives, Sustainable Construction, Fly Ash, Biopolymers, Agricultural Waste, Geotechnical Engineering.

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1. INTRODUCTION

1.1. Background

The Soil is the foundation of nearly all civil engineering infrastructures such as highways, buildings, embankments, airfields and retaining structures and hence the engineering behavior of the soil affects the safety and longevity of such systems directly. The soils in most of the natural environments have poor characteristics that include low carrying capacity, high compressibility, great potential of shrink and swell, as well as poor resistance of environmental activities i.e. variation of moisture and/or cyclic loading. Such incompleteness frequently results into structural distress through settlement, cracking and untimely failure. Introducing Soil stabilization thus is one of the ground improvement techniques aimed at altering and improving soil properties by mechanical, chemical or biological means, a purpose achieving a goal of enhancing strength, stiffness, workability and long-term performance of soils under service conditions. Traditionally, cement-cellular, lime-cellular, and bituminous single and combined methods based on chemical stabilization in case of taking the engineering structure on the geotechnical and pavement sectors have historically been the most widely used. Cement stabilization enhances the strength and durability of soil by placing soil particles together by means of hydration and cementation or lime stabilization with clay soils being the best to be stabilized by means of cation exchange, flocculation and pozzolanic reactions that make soils less plastic and thus more workable. Despite the effectiveness of these conventional stabilizers, which have been found to be very reliable, their manufacturing and operation have been characterized by great environmental handicaps. The production of cement is quite an energy-consuming process that accounts to about 78 percent of carbon dioxide emissions worldwide that contributes a significant level to climate change. The manufacture of lime also requires lot of high temperature calcinations that emit high amounts of CO 2. Increasing environmental awareness, tough sustainability targets and the necessity of decreasing the carbon footprint of the construction operation have thus made it more appealing to consider alternative and environmentally friendly ways of soil stabilization that will achieve the same engineering properties and yet have the least impact on the environment.

1.2. Need for Eco-Friendly Stabilization Techniques

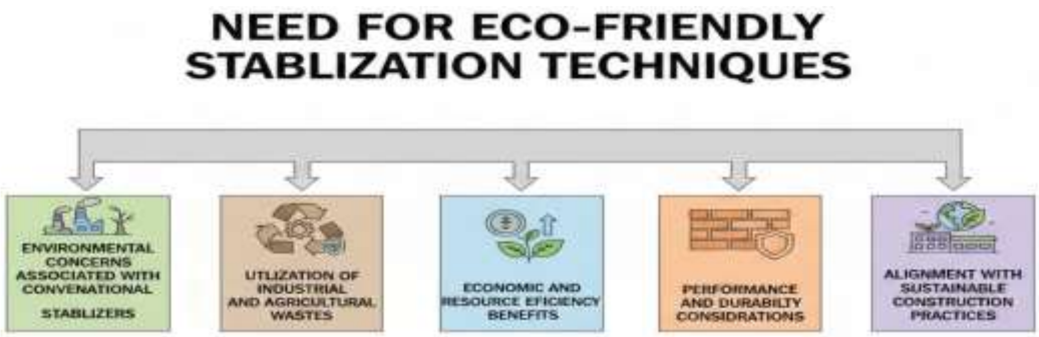

Fig 1 - Need For Eco-Friendly Stabilization Techniques

1.2.1. Environmental Concerns Associated with Conventional Stabilizers

The widespread application of the traditional stabilizing agents like cement and lime has caused serious environmental concerns because of their high-power consumption and carbon emission in the production process. More so, in cement manufacturing, limestone has to be subjected to very high temperatures leading to the massive emittance of carbon dioxide to the atmosphere. The massive use of such materials on geotechnical and pavement works is the source of greenhouse gas emissions, exhaustion of natural resources, and accelerated environmental degradation. These issues have given rise to heightened calls of sustainable alternatives that can make sustainability practices of soil stabilization process ecologically light.

1.2.2. Utilization of Industrial and Agricultural Wastes

Green stabilization method encourages the positive recycling of industrial by-products and agricultural wastes like fly ash, rice husk ash, slag, and bagasse ash. These are materials that end up being produced in vast numbers and become difficult to dispose and to the environment when they are not properly taken care of. They enhance the properties of soil engineering by ensuring that a higher amount of landfill is minimized, and that pollution is controlled as well. Eco-friendly stabilization is geared towards pro-cyclic economy and sustainable development as waste materials are converted into worthy construction products.

1.2.3. Economic and Resource Efficiency Benefits

The use of greener stabilizers could result in a great saving of costs since it would save on the use of costly traditional binders. Most of the waste-derived stabilizing products can be found locally and are relatively cheap hence they are especially appealing to large scale infrastructure developments in developing world. Also, it should be noted that decreased material transportation and the decreased energy consumption leads to the economic efficiency in general. These advantages bring about environmentally friendly stabilization methods as cost-effective and technology-wise feasible to develop infrastructure in the long-term.

1.2.4. Performance and Durability Considerations

In research, advancements have shown that environmentally friendly stabilizers could provide equal or better performance of the conventional techniques in terms of strength, environmental and continuous load resistance. Natural fibers and biopolymers can promote ductile behavior and crack resistance and bio-mediated methods give better soil bonding without use of toxic chemicals. These strategies provide better performance in the long term besides meeting the objectives of sustainability.

1.2.5. Alignment with Sustainable Construction Practices

The increased focus on sustainable and green buildings has only increased the pressure on the use of sustainable methods of soil stabilization. Policies on carbon emission, environmental policies, and international sustainability goals promote minimization of carbon emission and optimal use of resources. The eco-friendly stabilization techniques can be adapted to these goals and therefore use of a combination of both techniques is a significant part of the current geotechnical engineering practice.

1.3. Soil Stabilization Using Eco-Friendly Additives

The application of soil stabilization with the implementation of environmentally friendly additive as a method of soil stabilization has proven to be among such promising solutions capable of corroborating the shortcomings of traditional methods of soil stabilization and encouraging sustainability in geotechnical engineering. Mainly, the eco-friendly additives are the industrial by-products, agricultural wastes, natural fibers, biopolymers, and the bio-mediated agents, which are of great benefit to the environment and technology-wise. The materials are mostly waste by-products or renewable materials and therefore are economical and environmentally friendly as compared to the conventional stabilizers, cement and lime. Their use in the stabilization of soils does not only enhance the performance of the soils but also helps in the reduction of waste materials as well as the preservation of the natural resources. Fly ash, ground granulated blast furnace slag and silica fume are industrial by-products, which have pozzolanic or latent hydraulic properties allowing them to react with the soil minerals with the aid of moisture and activators. These reactions lead to the development of cementitious compounds which contribute to the increase of soil strength, stiffness and durability. On the same note, other wastes like rice husk ash and sugarcane bagasse ash, which are rich in amorphous silica, are strong pozzolans whose use is successful in decreasing plasticity and enhancing load-bearing ability of soils composed of clay. Disposal of agricultural residues which are linked to problems of waste is also a solution in the utilization of such materials. Natural fibers like coconut coir, jute and sisal help in stabilizing soil through mechanical reinforcement. These fibers can be combined with soil to enhance tensile strength, ductility and crack-resistance by binding the soil particles together, and limiting their deformation. Also, biopolymers like xanthan gum, guar gum, increase soil cohesion by creating binding networks that augment their interlocking of the particles especially in sandy and silty soils. Recently, bio-mediated practices have been noted to be used like microbial-induced calcite precipitation which improves soil strength using biological processes which are friendly to the environment as well. In general, eco-friendly additives as a soil stabilizing agent is both a comprehensive and environmentally friendly solution, which balances the engineering characteristics with environmental protection, thus it is very applicable in the development of contemporary infrastructure.

2. *LITERATURE SURVEY*

2.1. Industrial By-Products in Soil Stabilization

The use of industrial by-products as a stabilizer to soils has elicited extensive research investigations because of its economical nature, high volumes and the high gains it offers to the environment. One material in this category that has received the most researches is fly ash, which comes out of coal-fired thermal power plants. Fly ash is categorized as either Class C or Class F depending on their chemical composition. Class C fly ash has self cementing qualities that relate to the high calcium content in it that makes it to enhance the strength of soils without the need of external activators. Conversely, Class F fly ash, that is high in silica and alumina but low in calcium, needs activators to be used like lime or cement to trigger pozzolanic reactions. In many experimental studies there is a significant enhancement in unconfined compressive strength (UCS), California Bearing Ratio (CBR), and shear strength of expansive and soft clay soils with the incorporation of fly ash. Equally, ground granulated blast furnace slag (GGBS), which is an iron and steel industry side by-product, is latently hydraulic. GGBS, when it is used in combination with alkaline solution or calcium-based additives, is hydrated and undergoes pozzolanic reactions to produce cementitious compounds, which make the soils stronger and stiffer. The scholars have also indicated low permeability, increased durability and better resistance to chemical attack in GGBS stabilised soil and has been found to be useful in the pavement subgrades and foundation.

2.2. Agricultural Waste-Based Stabilizers

The agricultural waste products have been receiving growing attention as the sustainable soil stabilizers because of their renewable nature and limited environmental impact. Rice husk ash (RHA) is an amorphous silica with a high proportion produced through controlled burning of rice husks thereby rendering it a very reactive pozzolanaic material. It has been found that the addition of RHA to clayey and expansive soils has a great impact on lowering the plasticity index at the expense of raising the compaction properties and strength parameters. The best replacement levels of 10 percent to 20 percent have been found to be most effective in optimizing the UCS and CBR values and not negatively influencing the workability. Other than RHA, soya sugarcane bagasse ash (SCBA) and palm oil fuel ash (POFA) have shown to be promising in soil stabilization. It enhances the functionality of the soils, these materials fill the void spaces, and they also get involved in pozzolanic reactions in the presence of lime or cement. Indeed, experimental research studies conducted at the time indicate that the ashes of agricultural waste help to enhance load bearing capacity, swelling potential and long-term strength and therefore provide an alternative to traditional stabilizers which is environmentally friendly.

2.3. Natural Fibers and Biopolymers

Natural fibers and biopolymers should be used in the process of soil stabilization as environmentally friendly so that the soil behavior can be modified using mechanical and chemical procedures. Some biodegradable and locally available natural fibers that reinforce soils by holding the particles together include jute, coir, sisal, and bamboo, which are cheap. Fiber addition enhances tensile strength, ductility and after peak performance of soils resulting in an increased resistance towards cracking and brittle collapse. Research has shown that it is the fiber-reinforced soils which are characterized by enhanced shear strength as well as enhanced characteristics of stress-strain, especially during cyclic and dynamic loading environments. Simultaneously, bio polymers including xanthan gum, guar gum and lignin-based binders have come up as innovative stabilizers of soil since they have the ability to bind. These biopolymers create sticky gels which coats and attaches particles in soils, enhances soil cohesion and minimises vulnerability to erosion. It has been demonstrated that biopolymers treated sandy and silty soils undergo profound changes in the strength and stiffness without losing permeability. Their not being toxic and biodegradation make them suitable to temporary and sensitive applications with regards to the environment.

2.4. Bio-Mediated Soil Stabilization

Another new environmentally friendly and novel method of soil stabilization involves bio-mediated soil stabilization, especially the microbial-induced calcite precipitation (MICP). This method is based on the metabolic activeness of certain bacteria e.g. the ureolytic microorganisms which trigger the precipitation of calcium carbonate in soil pores. The resultant bio-cementation cement holds the soil particles in place resulting to increased stiffness, strength and decreased permeability. Rawberg et al. (2003) have found remarkable enhancement in the unconfined compressive strength, shear resistance and erosion control in Sandsy and granular soils which are treated with MICP in experimental research. In comparison to traditional stabilizers, bio-mediated techniques do not use harmful chemicals hence environmentally harmless. Nevertheless, their demonstrable effectiveness is accompanied by issues that concern the ability to scale, the consistency of treatment, bacterial resilience, and cost; they are the key obstacles to the broad field usage. Continued studies are put on the effort of maximization of bacterial strains and nutrient delivery systems as well as treatment procedures to enhance the efficiency of each procedure and its practicability. With the solutions to these challenges in place, the process of bio-mediated stabilization solutions will become very significant in sustainable geotechnical engineering process.

3. METHODOLOGY

3.1. Materials Used

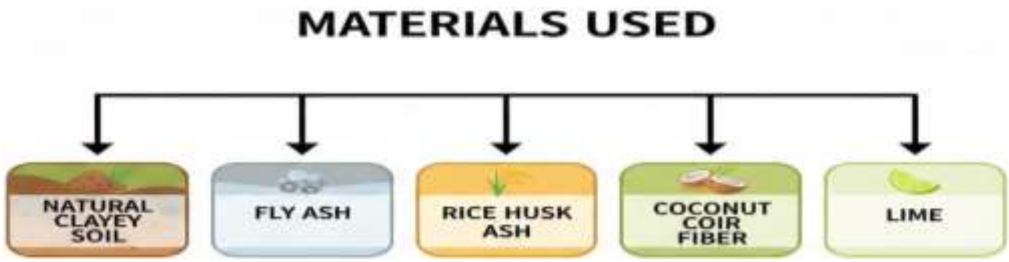

Fig 2 - Materials Used

3.1.1. Natural Clayey Soil

The soil applied in this research was natural clayey soil of a local area where I collected the soil and used it as a base on which to test the effect of stabilization. The soil is mainly composed of fine-grained particles that are relatively plastic, which leads to ability to change volume, low strength and the lack of credibility of its load bearing capacity in different moisture levels. These features elevate clayey soils to the position of agreeable subjects of the research on the studies of soil stabilization because the enhancement of strengths, plasticity and durability are easily realized with the use of stabilizing agents.

3.1.2. Fly Ash

Fly ash is an industrial by-product that came out a result of the high-temperature burning of coal in a thermal power plant and was utilized in this experiment as an addition to cementitious material. It also includes reactive silica and alumina, which enter into pozzolanic reactions with mixed climate with soil, including moisture and lime. Fly ash increase is helpful in contributing to the strength

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of soil, plasticity, and compaction properties. It is also helpful in occupying soil voids since it has a very fine particle size, resulting into the creation of denser and firmer soil matrix.

3.1.3. Rice Husk Ash

The Rice husk ash is an agricultural waste, which is formed as a result of controlled burning of rice husks. It contains a high amount of amorphous silica and thus is a good pozzolanic soil stabilizer. In this analysis, the rice husk ash was used to partially substitute soil to enhance the engineering properties. Incorporation of rice husk ash also leads to decreased plasticity, increment in strength, and resistance to deformations due to moisture, thus contributing to environmental friendly construction.

3.1.4. Coconut Coir Fiber

Coconut coir fiber is a natural biodegradable fiber which is obtained as the husk of coconuts and was utilized as a reinforcement element in the soil. The fibers offer mechanical interlocking to the soil matrix and enhance tensile strength, ductility, and cracking resistance. Coir fiber has a high lignin content therefore it is very durable and slow to degrade, and thus can be used in replacing the soil in short- to medium-term.

3.1.5. Lime

Lime is an ancient stabilizer of soils very common to enhance the engineering qualities of clayey soils. Lime when incorporated into soil triggers cation exchange and pozzolanic reactions, therefore, leading to a decrease in plasticity, strength, as well as enhanced workability. In this experiment, lime was not only utilized as a primary stabilizer in the study but it was applied as an activator to the fly ash and rice husk ash so that the formation of cementitious compounds could be achieved which contributes to the stability and overall performance of the treated soil.

3.2. Sample Preparation

The soil samples were prepared in a systematic and controlled way to ascertain consistency and replication of the test results. The samples of clayey soils collected were first air-dried in room temperature to eliminate the natural moisture content of the soil without changing the mineralogical properties of the soil. Caution was taken against oven drying since too much heat can cause changes in clay structure and reactivity. The dry soil was then lightly ground up and sieved through a 4.75 mm IS sieve to remove the gravel-sized particles and be left with a homogeneous fine-grained soil to be used in stabilization studies. This sieved soil was used as the foundation of all the further sample preparations. The stabilizing additives, i.e. fly ash, rice husk ash, coconut coir fiber and lime were added to the soil at the set proportions depending on the weight of the dry mass. After determining the weight of each additive, it was weighed with a digital balance and the weight was given with the least amount of error in an attempt to reduce experimental error. In case of composite mixtures, dry mixing was conducted in detail so as to reinforce the mix of additives through the soil matrix. With coconut coir fiber the fibers were chopped to a length that was exactly the same and evenly distributed as much as possible in order to eliminate balling or clustering because this would result in non uniform reinforcement and strength behavior. Potable water was then added gradually to the soil-additive

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mixture after the mixture had dried out. The potable water was added to ensure an optimum moisture content of the mixture as established in qualitative Proctor compaction tests. Water was introduced gradually in steps and mixed continuously until the circulation of water was evenly distributed on the sample. The wet mixture was left to mellow in the short-term, especially when using lime-treated samples, to enable early reactions between the chemical components like cation exchange and flocculation. The ready mixtures were pressed into standard moulds with the help of standard Proctor energy in accordance with the applicable test codes. Compaction was done in layers, and the number of blows applied to each layer was equal to generate the homogeneous density. The extrusion was done on the compacted specimen, labeled and placed in airtight conditions before testing and curing. This standard preparation process made the preparation process to be consistent across any specimen and the effect of various stabilizing materials on soil performance could be compared.

3.3. Laboratory Testing Program

Fig 3 - Laboratory Testing Program

3.3.1. Atterberg Limits

Atterberg tests were done to determine the consistency and plasticity of the untreated and stabilised soil samples. The tests involved the liquid limit, plastic limit determination, and plasticity index to determine the modifications done in the workability and compressibility of soils with the introduction of stabilizing agents. The outcomes offered an understanding on the effectiveness of fly ash, rice husk ash, lime, and coconut coir fiber in alleviating soil plasticity and modifying its appropriateness to engineering works.

3.3.2. Normal Proctor Compaction Test

Proctor compaction test was the standard test that was done to establish the optimum moisture content and maximum dry density of the soil and stabilized mixtures. The test was useful in perceiving how various additives affect compaction behavior. The differences in the dry and moisture density requirements reflected the alteration of soil structure and particle distribution with stabilization which are important in the control of field compaction and Fortune of construction quality.

3.3.3. Unconfined Compressive Strength Test

The unconfined compressive strength (UCS) test was conducted to determine how the strength of soil specimens will be improved due to the stabilization process. The axial compression of the cylindrical samples was done without any resulting lateral confinement to permit a direct assessment

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of load bearing capacity. The UCS outcomes were employed to measure the value of a single and collective stabilizer in improving the strength and stiffness of soil in the course of various curing time.

3.3.4. California Bearing ratio Test

California bearing ratio (CBR) test was carried out in order to determine the load-bearing capacity of the stabilized soil especially when used in pavement and subgrade. Unsoaked and soaked CBR tests were conducted in order to determine sensitivity of moisture tests. Increase in values of CBR meant an increase in resistance to penetration and increased performance in traffic loading condition.

3.3.5. Durability Tests

Stabilized soil was tested in terms of durability to determine the performance of stabilized soil in the unfriendly conditions. Such tests were usually subjected to wetting/drying or freezing/thawing cycles to expose the tests to field conditions. The findings were an informative source on the strength degradation, disintegration, and volumetric instability resistance of treated soil and guaranteed the effectiveness of the stabilization method in the service service till it lengthens.

3.4. Performance Evaluation Parameters

Fig 4 - Performance Evaluation Parameters

3.4.1. Strength Gain

One of the main parameters that were employed in determining the effectiveness of soil stabilization was strength gain. It was measured by determining the increase in the values of the unconfined compressive strength and the California Bearing Ratio of the treated soil samples against that of the untreated one. Increase in the level of strength is a sign that the cementitious bonds have been formed as a result of the pozzolanic reactions and the strengthening of particle interlocking through the stabilizing agents like fly ash, rice husk ash, lime and coconut coir fiber. The increase in strength is a measure of the better load bearing and structural stability of the stabilized soil.

3.4.2. Reduction in Plasticity Index

The plasticity index was reduced as the indicator of enhanced soil workability and decreased volume change behavior. The breakdown of the clay mineral structure of the soil by the added stabilizing material as a result of exchanging and flocculating cations results into the reduced values of the liquid limit and the plasticity index. A lower plasticity index would indicate a low degree of

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being susceptible to shrink swell behavior and good handling qualities that are necessary in construction of clayey soils.

3.4.3. Increase in Bearing Capacity

The bearing capacity increase was tested mainly by the results of California Bearing Ratio test. Increased CBR values show better resistance to penetration, and increased capacity of the soil to carry loads especially in subgrade pavement and foundation construction. This assists in the introduction of stabilizing agents, which enhances the density, hardness and bondage between particles of the soil, and therefore, enhances the soil to balance and allocate the loads applied to the soil effectively.

3.4.4. Resistance to Moisture-Induced Deterioration

The capacity to oppose the corrosion caused by moisture was evaluated by way of the durability based observations and the soaked strength tests. The stabilized soils have been tested in terms of the strength and structural meaning when they were subjected to water or cyclic wetting and drying. Increased resistance is the sign of decreased permeability, better bonding, and higher stability that makes the stabilized soil maintain a good performance under different environmental and moisture conditions.

3.5. Governing Equations

The analysis of the strength and load-settlement of the stabilized soil in this experiment, was majorly analyzed using the unconfined compressive strength (UCS) and California Bear ratio (CBR) tests, which are common parameters of geo-technical engineering. Unconfined compressive strength is defined as top compressive stress of soil which is supported by stress due to axial compressing, without stress being supported by confinement (lateral). It is calculated by dividing the total axial load at the point of failure and volume of the surface of the specimen that is corrected. Practically, the axial load is the highest load measured in the compression test, and the corrected area takes into consideration the increment of the diameter of the specimen due to the axial deformation of the same during loading. This is necessary in order to have a true estimate of actual compressive stress weighing within a specimen. The resultant UCS value which in most cases is expressed in kilopascals is a direct measure of how effective the stabilization is in enhancing the strength of the soil. On the same note, California Bearing Ratio is applied in determining the load-bearing capacity of soil Particularly on pavement and subgrade. CBR value measures the percentage and computed by dividing the load needed through the sample of stabilized soil in a standard depth by the load needed through a standard crushed stones material multiplied by a hundred. Penetration loads are usually tested on the standard penetration depths, e.g. 2.5 mm and 5.0 mm and the greater of the resulting ratios is used as the CBR value. The parameter gives a comparative value of the soil resistance to penetration under controlled circumstances. The two equations, UCS and CBR, are combined when the results in soil performance are to be determined as a result of stabilization. The effect of fly ash, rice husk ash, coir fiber, coconut and lime on the strength development and carrying capacity can be evaluated in a systematic manner by comparing the values they produce on the untreated and treated soil samples. These governing

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relations stabilize laboratories reading consistency and are utilized in assessment of stabilized soils to be used in engineering.

4. RESULTS AND DISCUSSION

4.1. Effect on Plasticity Characteristics

The integration of green stabilizing additives led to a great gain on the plasticity properties of the clayey soil. The untreated soil had a high liquid limit and liquidity index due to which it had high plastic behaviour and was highly prone to volume change when exposed to changes of moisture. These properties are not preferred in terms of engineering use because they cause excessive cases of shrink, swell and lowered workability. These consistency properties were significantly modified by the addition of both rice husk ash and fly ash and consequently, liquid limit and plasticity index were significantly reduced. The mechanism of decreasing plasticity may be mainly as a result of physicochemical reactions between the clay particles and the additives that make it stabilized. Fly ash, especially in combination with lime, provides calcium ions, which substitute the weaker monovalent ions weakening the surface of clay minerals in the process of cation exchange. This operation causes a flocculation and agglomeration of the clay particles into a small size that is more stable and slender non-metallic encasement. Consequently, the soil texture or structure becomes less dispersed resulting to less plasticity and enhanced workability. In the same manner, rice husk ash, which contains a high amorphous silica content, helps participate in pozzolanic reactions that also alters the soil matrix by over time creating cementitious compounds. The overall effect of flocculation and cementation of the soil is decreasing the affinity of the soil to water hence decreasing the liquid limit. The plastic limit, however, either rises marginally or is comparatively stable leading to a general reduction in plasticity index. The observed changes in the Atterberg limits are indicative of the change of the soil in a more friable and stable situation than the highly plastic one. These enhancements are especially helpful in the construction sector in that lower plasticity levels increase the effectiveness of compaction, decrease moisture sensitivity and increase handle properties. On the whole, the noted decrease in plasticity index proves effectiveness of eco-friendly additives, e.g. rice husk ash, fly ash in changing the underlying behavior of clayey soils. Such enhancements help improve the dimensional stability and durability to provide the appropriateness of sustainable stabilizers in geotechnical and pavement engineering applications.

4.2. Strength Improvement

The stability of the compressive strength outcomes as shown by unconfined compressive strength (UCS) test clearly showed the significant change in the strength characteristics of the stabilized clayey soil as compared to the untreated soil. The strength improvement was seen to be between about 40, and as high as 180 percent depending on the type and the dosage of the eco-friendly additive used. This variety of enhancement demonstrates the fineness of soil strength to the ratio and mix of stabilizing agents, and the interaction mechanism of the strength development. The introduction of the fly ash and the rice husk ash assisted a lot in strength acquisition by workshop of pozzolanic reactions, which consequently resulted to the cementitious products, which held the soil particles together and enhanced the entire stiffness. Calcium Lime was a very important element that promoted rapid

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increase in strength by catalyzing the cationic exchange and release calcium ions required in the process of pozzolanic activity. As the curing time increased, the further development of calcium silicate hydrate and calcium aluminate hydrate compounds led to the gradual increase of the strength. This trend in behavior was more pronounced in specimens with large proportions of additives of an ash base since long-term strength gain was more prominent than strength development at an early age. Better bonding of particles decreased the pore space and also increased the load transfer in the soil matrix, resulting in an increased compressive resistance. Stabilised soil was further altered, with coconut coir fiber that also altered the failure behavior of the soil. Fiber-reinforced specimens responded to the failure mode more smoothly and ductilely as compared to untreated soil which in most cases responded to abrupt and unsteady failure at the peak load. The fibers served as discrete reinforcing units which sewed growing cracks and limited their continuation under the axial load. The effects of this were enhanced retention of post-peak strength and augmentation of energy absorption ability. The fiber-reinforced soil still showed residual strength after the peak stress had already been reached, which means that the toughness and deformation capacity increased. On the whole, the UCS findings prove that the joint application of eco friendly stabilizers does not merely enhance compressive strength but also generates a change in the mechanical behavior of clayey soil whereby as it is currently brittle it turns into ductile. These are especially beneficial to geotechnical engineering where strength as well as deformation behaviour are paramount to long term stability and serviceability.

4.3. Bearing Capacity Enhancement

The outcomes of a California Bearing Ratio (CBR) test were of tremendous improvement in the bearing capacity of the stabilized clayey soil and pointed to its increased suitability as a pavement subgrade material. The poor penetration resistance and minimal load carrying ability of the untreated soil under traffic loading conditions have been manifested through the relatively low values of CBR. Nevertheless, adding stabilizing additives that are environmentally friendly resulted in the significant enhancement of both soaked and unsoaked CBR values. This is as a result of the combined effect of increased density, stronger inter-particle bonding as well as development of cementitious compounds in the soil matrix. Amongst different stabilizer blends that were tested, fly ash-lime mixtures were found to be the best in increasing the CBR values. Lime was present and provided calcium ions which caused the release of the pozzolanic potential of fly ash and formed calcium silicate hydrate and calcium aluminate hydrate compounds. These products of reactions occupied stubs that existed between soil particles and formed a consolidated, interlaced framework with the capability to distribute well applied loads. Consequently, the stabilized soil had a high penetration resistance than soil that was subjected to individual additives. The ash of rice husk was also beneficial to the increase in bearing capacity although its use with lime was beneficial. The presence of large quantities of amorphous silica in ash of rice husk also favored the secondary pozzolanic reactions, which further enhanced the strength of the skeleton of soil, in the long run. Further, the addition of coconut coir fiber made slight enhancements in the CBR performance through barring deformation and also the transfer of loads during penetrations. Although the directly reinforcing effect of fibers was not immediate in cementation, they enhanced this property of soil still in loading. The better CBR performance indicates that stabilized soils are able to provide the pavement subgrade strength requirements and minimize the thickness of the overlying layers of pavement. Moreover, the increased soaked CBR values reflect the increased resistance to the weakening effects of moisture which is vital in the long run pavement performance. All in all, the increase in bearing capacity due to fly ash lime stabilization shows the technical feasibility and the financial merit of applying environmentally friendly materials in road construction activities that raise the level of sustainability.

4.4. Durability Performance

The sustainability performance of the environmentally friendly stabilized soils was tested by the way they reacted to several wetting-drying processes, which is the environmental condition the soils are likely to undergo in the field. The clayey soil without treatment exhibited apparent degradation to the cycles, which included cracks of the surface and loss of cohesive action and a considerable decrease in strength. This kind of action commonly occurs in soils that are highly plastic in nature and are prone to changes in moisture that lead to repeated swellings and contractions. However, the opposite was seen with the soils that had been modified using environmentally-friendly stabilizing agents in the sense that they were found to be more resistant against the effects of moisture in degrading them visibly. This enhanced stability is due to the development of stable cementitious compounds as a result of primary reactions between fly ash, rice husk ash and lime as pozzolans. The binding phases formed during these reactions were calcium silicate hydrate and calcium aluminate hydrate and increased the bond of the particles and decreased permeability of the soil matrix. Consequently, wetting stages resulted in a reduced water uptake, which reduced volumetric alterations, and ensured no structural degradation occurred during the drying stages. The mass loss and strength decrease after several cycles were minimal in stabilized specimen with fly ash and lime, thus being the most resistant to environmental exposure. Rice husk ash was also found to give positive effects on the durability performance as it refined the pore structure and it minimised the continuity of the capillary voids. This effect aided in the limiting the movement of moisture in the soil hence reducing the destruction of the soil through the drying and wetting cycles. Also, coconut coir fiber led to better durability by reinforcing the product mechanically and limiting cracks formation and spread. The fibers formed tensile bridges over growing micro-cracks assisting the soil to maintain its integrity despite the recurrent environmental loads. All-in-all, better performance and reliability long-term are provided by the increased resistance to wetting-drying cycle in the eco-friendly stabilized soils. This kind of durability is important where the soil is subjected to different moisture and temperature conditions that occurs constantly, geotechnical and pavement applications. The results prove that sustainable stabilizers do not only enhance the short term strength but also provide structural stability and service life under unfavorable environmental conditions within a long period of time.

5. CONCLUSION

This paper conclusively shows that the deployment of environmentally friendly additives is a sustainable, cost-effective and technical effective approach towards enhancing the engineering characteristics of challenging clayey soils. The addition of industrial by-products like fly ash and farming wastes like rice husk ash played a great role in improving the performance of the soil as it made it stronger and less plastic and made it resistant to breakages due to moisture. Major contributions to these enhancements are explained by the following physicochemical processes including; cation exchange, flocculation, and pozzolanic processes, which alter the weak and extremely plastic soil into more solid and load-bearing substances that can be used in engineering works. According to the results of the experiment, it is obvious that the combinations of fly ash-lime are especially effective in improving the values of unconfined compressive strength, as well as in California Bearing Ratio. Cementitious compounds like calcium silicate hydrate and calcium aluminate hydrate are formed which enhances the bonding of particles, decreased permeable and increased in undergoing cyclic wetting and drying environments. On the same note, rice husk ash was found to be a viable pozzolanic substance which increased not only strength properties of the material but also ensured a sustainable construction process since ash was made using agricultural waste, which would otherwise be expensive to dispose. The change in plasticity index in stabilized soils shows the difference in the behavior and increased workability as well as decreased shrink swell behavior which is of critical importance in the long-term behavior of pavements and foundation systems. Added natural coconut coir fiber contributed to better mechanical response of stabilized soils through the increase in ductility and post-peak behaviour. Fiber-reinforced samples had a slow failure behavior and increased energy absorption ability with respect to the brittle failure behavior of the untreated soils. This deformation behavior has been improved especially in situations where the soils are prone to repeated loading or settlements differing with each other. Also, the bio-mediated soil stabilization methods though being at the initial stages of development have immense potential because of their environmentally friendly nature and the capacity to increase the soil strength without incorporating toxic chemicals. In general, the findings confirm that green building methods of soil stabilization may be utilized successfully to substitute or complement traditional stabilizers like cement and lime in most geotechnical and pavement construction. Such sustainable means will help to minimize carbon emission, utilize the waste efficiently, and become better stewards of the environment. The next-generation research needs to be done in the field implementation on a large scale, long-term performance, and life-cycle cost analysis to prove the laboratory research. More bio-based and hybrid stabilization techniques will have to be optimized and the design and construction guidelines will have to be standardized to encourage the broader usage and effective implementation of the eco-friendly technologies of soil stabilization.

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