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Investigation on the Synergistic Behavior of Cement, Copper Slag, and Phosphogypsum in the Stabilization of Black Cotton Soil

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Abstract

The current research aims at stabilizing expansive black cotton soil through the use of a ternary mixture of Ordinary Portland Cement (OPC), Copper Slag (CS), and Phosphogypsum (PG) that might be providing good results with minimal resource utilization by the materials. The selection of the three materials was made keeping in mind a synergistic effect that could be achieved. For instance, a) cement is the main binder, b) copper slag is a pozzolanic activator, and c) phosphogypsum is a source of ettringite. Black cotton soil was amended with different proportions of the ternary blend and its performance was assessed through Atterberg limits, Free Swell Index (FSI), and Unconfined Compressive Strength (UCS) tests. The optimal blend was the one that produced the highest strength and most reduction in swelling characteristics. In fact, with the increase in the addition of the ternary stabilizer, the liquid limit and plasticity index were reduced consistently, whereas the shrinkage limit was increased, signifying an enhancement in the volumetric stability of the soil. A substantial decrease in the free swell index, at the level of about 73%, was achieved by the optimal blend with respect to the untreated soil. The UCS was increased by almost 375% at the optimal mix in comparison with the untreated soil after 60 days of curing. The pozzolanic reaction and the gradual development of C-S-H, C-A-H, and ettringite phases were the underlying reasons for this strength. These results corroborate the notion that the ternary mixture as proposed herein is a feasible and efficient method for the stabilization of expansive black cotton soils.

Keywords: Expansive black cotton soil; Ordinary Portland Cement (OPC); Copper Slag; Phosphogypsum (PG); Pozzolanic reaction; Shear strength improvement

INTRODUCTION

Expansive soils, especially black cotton soils (BCS), are found in many parts of India and other semi-arid areas in the world. These soils contain a lot of smectite, a type of clay mineral, which is why they swell and shrink notably when moisture changes. Such large variation of volume leads to, among the other things, the destruction of roads, pavements, foundations, and embankments. The financial losses caused by expansive soils to civil engineering structures are huge every year being so dangerous that stabilizing them has become very important in geotechnical engineering (Ankit et al., 2020; Patel and Shahu, 2021). Among various ways to stabilize soil, chemical additives have proved to be very effective. Lime and Ordinary Portland Cement (OPC) are traditional stabilizers that have been applied to expansive soils for a very long time. These materials which are calcium-based encourage the pozzolanic and cementitious reactions of the soil thereby changing its mineralogical composition and micro-structure. It brings about the reduction of soil plasticity, decrease of its swelling capacity, and enhancement of its strength features. On the other hand, the fact that the cost of these conventional items is constantly increasing, and the environmental aspect of their production (especially the large carbon dioxide emission from the manufacture of cement) have driven the researchers to identifying other supplementary and alternative stabilizing agents that are not only cheap but also environmentally friendly (Moghal et al., 2021; Kumar and Sharma, 2022). In this regard, the use of industrial by-products to replace conventional stabilizers partially has, in recent years, become a very method in the geotechnical field. This method, on the one hand, gets rid of the problem of waste disposal and, on the other hand, it helps reduce the environmental impact of construction materials. Out of the various waste materials that have been studied, copper slag (CS) and phosphogypsum (PG) are considered quite good due to their chemical composition and the possibility of having, one way or another, a reaction with cementitious materials (Murari et al., 2015; Qureshi et al., 2015).Copper slag is one of the wastes obtained at the stage of smelting and refining copper ore processing. Generally, the amount of copper slag produced is around 2.2-3 tonnes for every tonne of copper metal, and since copper production worldwide is expected to be over 20 million tonnes in a year, the total amount of copper slag generated is very large (ICSG, 2018). Copper slag contains major amount of iron oxide, silica, alumina, and calcium oxide that when combined together can make copper slag capable of undergoing pozzolanic reactions provided activators like lime or cement are present. Due to the very high angularity and friction angle of copper slag particles, soils mixed with copper slag show a considerable rise in their shear strength (Zhang et al., 2018). The fact that copper slag is deemed non-hazardous both by Indian environmental laws as well as by the Basel Convention also endorses its use as a construction material (Alter, 2005).

Phosphogypsum is a calcium sulfate dihydrate ($CaSO_4{\cdot}2H_2O$) obtained as a by-product during the wet- process manufacturing of phosphoric acid from phosphate rock. For every tonne of phosphoric acid produced, roughly 4 to 5 tonnes of phosphogypsum are generated, resulting in enormous stockpiles worldwide that pose serious threats of land and groundwater pollution (Tayibi et al., 2020). However, phosphogypsum is also endowed with some very good engineering properties. Calcium sulfate in phosphogypsum interacts with calcium aluminate hydrates resulting in the formation of ettringite ($3CaO{\cdot}Al_2O_3{\cdot}3CaSO_4{\cdot}32H_2O$), a crystalline phase that is stable and has the ability to refine pore structure of soils, and also contribute to strength development (Jiang et al., 2021). Besides, few recent studies have shown that phosphogypsum can lower the volume change of swelling soils and at the same time, it can act as a sulfate activator that facilitates pozzolanic reactions in the systems containing slag (Rahman et al., 2022).Using the OPC, copper slag, and phosphogypsum as a three-way stabilizer system combine to make a very strong ternary stabilizer system based on complementary chemical premise. Cement, the primary binding agent and the supplier of calcium hydroxide ($Ca(OH)_2$) generated during the cement hydration. This released calcium hydroxide will then come in contact with the silica and alumina from the copper slag through secondary pozzolanic reactions to produce the gels of calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H). At the same time, the sulfate coming from the phosphogypsum reacts with the aluminous phases to produce ettringite and gypsum-based compounds, which not only fill the inter-particle voids but also result in a soil fabric that is denser and more interlocked. This cooperative interaction between the three ingredients should, by theory, produce a better engineering performance than the use of any single or binary combination of stabilizers (Jiang et al., 2021; Moghal et al., 2021).

A huge amount of research work has been dedicated to binary stabilizer combinations for the black cotton soil treatment. Lime, fly ash, cement, rice husk ash, and lime, slag mixtures experiments have not only helped in confirming the improvements in Atterberg limits, unconfined compressive strength (UCS), California Bearing Ratio (CBR), and swelling behavior (Kumar and Sharma, 2022; Ankit et al., 2020), but these types of stabilizer pairs have been tested at the pilot plant level as well. On the other hand, research works about the ternary stabilizer systems that use copper slag and phosphogypsum along with cement for black cotton soil treatment are very few in the literature. The chemical interactions between copper slag and phosphogypsum in cement-stabilized expanded soil environments and especially how the formation of ettringite controls swelling are not well established. Addressing this gap is not only a scientific challenge but also a practical one for geotechnical engineers who want to develop stabilization solutions that are cost-effective and that have the added benefit of waste-valorizing.

Nowadays, characterization of stabilized soils through advanced microstructural and chemical analyses has become a very important aspect of geotechnical research. With the help of X-ray diffraction (XRD), one can obtain the qualitative and semi-quantitative data of the crystalline phases which help to identify the reaction paths that lead to strength development and swell reduction. Another technique, Scanning Electron Microscopy (SEM), helps to see the changes in the soil fabric directly such as the formation of cementitious products, pore filling by reaction compounds, and bonding of particles. These two above techniques illustrate detailed and precise mechanisms of stabilization which are also supported by macroscale engineering tests (Patel and Shahu, 2021; Rahman et al., 2022). Thereby, the current research work was carried out in view of studying the combined effects of a ternary mixture Portland Cement, Copper Slag, and Phosphogypsum as stabilizers of black cotton soil.The main goal is to determine the right amounts of this three components mixture that lead to the highest enhancement of geotechnical properties such as UCS, Atterberg limits, CBR, and free swell index. Microstructural analysis through XRD and SEM are also done in order to make a little sense of the chemical reactions responsible for the observed results. Eventually, this research intends to promote the ternary stabilizer as a practical, green, and economical substitute for the conventional chemical stabilizers in the treatment of expansive soils.

MATERIALS USED. This section describes the physical, chemical and index properties of three different materials that were the focus of the stabilization research: black cotton soil, copper slag, with two stabilizing agents, Ordinary Portland Cement (OPC) and Phosphogypsum (PG).

Black Cotton Soil. The swelling soil for this research is a type of black cotton soil one of which montmorillonite is a major component. Montmorillonite is a clay mineral that swells to a large extent. A set of normal laboratory tests was conducted to find out the physical and index properties of the soil samples. The results are given in Table 1. The elemental oxide composition of the soil is shown in Table 2. A scanning electron microscopy (SEM) study was carried out to understand the micro-level arrangement of particles. It is evident from Fig. 1 that the soil s a very loosely packed setting with large inter-particle voids. Weak Van der Waals forces and the presence of exchangeable cations which partially compensate the charge deficiency of clay platelets are factors for such an arrangement. This very weak bonding between particles makes the soil very susceptible to moisture penetration. Moisture penetration causes volume change i.e. swelling of the soil which is typical of this type of soil.

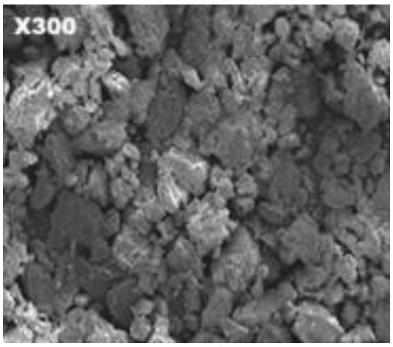

Figure 1 SEM Image of Black Cotton Soil

Table 1 Index and Physical Properties of Soil and Copper Slag

Property	Soil	Copper Slag
Specific gravity	2.7	3.7
Liquid Limit	66%	-
Plastic Limit	22%	Non-Plastic
Plasticity Index	44%	Non-Plastic
Gravel	1%	2
Sand	9%	95
Silt	26%	3
Clay	64%	-
Classification	High Plastic Clay	Poor Graded Sand
Maximum Dry Density (g/cc)	17%	7%
Optimum Moisture Content (OMC)	1.64 g/cc	2.55 g/cc
Unconfined Compressive Strength at OMC	178 kPa	-

Table 2 Chemical Composition of the Admixtures

Property	Soil	Copper Slag	Phosphogypsum	OPC
SiO_2 (%)	71.72	6.94	4.99	19
Al_2O_3 (%)	11.3	12.96	1.94	4.5
Fe_2O_3 (%)	7.11	67.88	1.08	3.5
CaO (%)	2.64	6.19	37	62.5
K_2O (%)	0.95	0.62	0.29	0.7
MgO (%)	2.27	0.95	0.48	2.5
CO_2 (%)	1.87	3.46	53	2.5
Na_2O (%)	0.81	0.1	Trace	0.2
TiO_2 (%)	1.33	-	0.27	-
P_2O_5 (%)	-	-	1.53	-

Copper Slag.A by-product of copper refining, copper slag is essentially a dense, dark, glassy granule-like material. Table 1 attributes its remarkably high specific gravity of 3.68 mainly to the presence of iron, as iron-containing compounds have much higher unit weights than most other mineral components. The copper slag grain size distribution lies within the range of a medium-sized sand. The chemical composition of the oxides is given in Table 2, where the main components constitute SiO_2, Al_2O_3, Fe_2O_3, and CaO. No sulfates were found in the slag, which means chemically it is very stable and there will be no risk of super-expansion due to sulfate. The total amount of silica, alumina, and iron oxide is more than 87%, which is higher than 70%, which is an indication for materials that will produce effective pozzolanic compounds according to ASTM C618 (ASTM, 1999). Copper slag was found to have a very low water absorption of only 0.5%, which is indicative of its dense, practically impermeable glassy phase. The SEM photograph in Fig. 2 discloses the typical very angular form of copper slag particles with quite sharp edges, which is a property that results in high inter-particle friction and soil shear resistance.

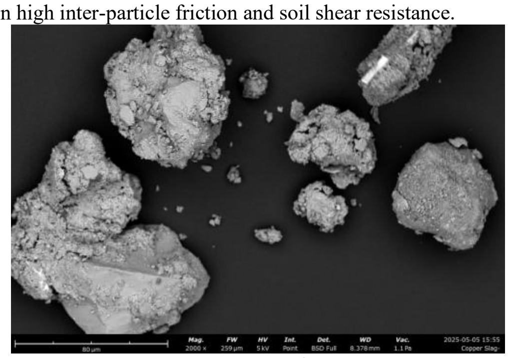

Figure 2 SEM Image of Copper Slag

Phosphogypsum (PG) Phosphogypsum is a type of industrial waste that is rich in sulfate and is a co-product of the production of phosphoric acid by the wet process of converting phosphate rock. In terms of its chemical composition, it mainly consists of calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$) with small amounts of leftover phosphates, fluorides as well as trace impurities as indicated in its chemical composition shown in Table 2. Phosphogypsum, with regards to soil stabilization, carries out a very different and supports the role of other chemicals. Sufficient uptake of sulfate ions by the phosphogypsum, leads to a reaction with calcium aluminate hydrates which were made available from cement hydration to produce ettringite ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$) that is a stable, needle-shaped crystalline phase. Ettringite formation into the network of soil pores brings about a decrease of void ratio and improvement of bonding between the particles which in turn results in less swelling and higher load-bearing capacity. Besides this, phosphogypsum's calcium content can be used to create a supplementary activating environment which will help in bringing out latent pozzolanic activity in copper slag. Physical features like specific gravity and particle size of phosphogypsum with which is shown in Table 1. The SEM image of phosphogypsum is given in Figure 3.

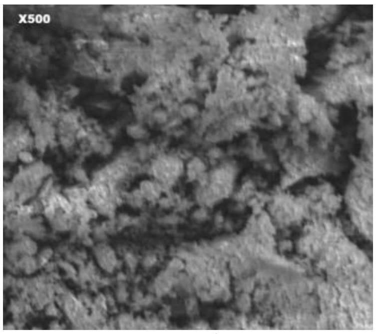

Figure 3 SEM Image of Phosphogypsum

Ordinary Portland Cement (OPC) Ordinary Portland Cement of 43-grade that complies with IS 8112 was the main binder used for this work. Table 2 lists the chemical composition of the OPC used. Cement was chosen because it can quickly start hydration reactions once it comes into contact with water, resulting in the production of calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) gels in addition to free calcium hydroxide ($Ca(OH)_2$). This released portlandite has two different functions: on one hand, it is directly involved in early strength development through cementitious bonding, and on the other hand, it acts as an alkali activator that stimulates secondary pozzolanic reactions with the silica and alumina in the copper sludge. The overall outcome is a gradual strengthening of the soil framework because cementitious reaction products fill the spaces between the particles. The physical characteristics of OPC such as specific gravity and fineness are given in Table 1. The SEM image of cement is given in Figure 4.

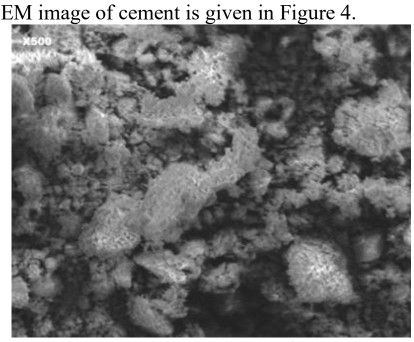

Figure 4 SEM Image of OPC

Hence, the four materials as a whole carry out by working together: cement offers the main framework of the binding medium and the environment of alkaline activation, copper slag brings extra pozzolanic phases, and phosphogypsum leads ettringite formation while at the same time increases sulfate-activation of slag. Altogether, these form the foundation of the ternary stabilization system which has been the subject of this research.

METHODOLOGY

Sample Preparation. The black cotton soil obtained from the field was exposed to air drying in the lab to get rid of any moisture and was broken down with a rubber mallet to separate the aggregates especially if they were clumped. Then the soil was pulverized and sieved through a 4.75 mm IS screen to remove any large particles and to ensure that test specimens are of similar size. The finished soil was placed in airtight jars so that it doesn't absorb any moisture inadvertently before the testing. Copper slag was directly delivered from a copper smelting works and being in a granular, free-flowing form, the copper slag didn't require any further processing before use. The Ordinary Portland Cement (43-grade, following IS 8112 standards) as well as the Phosphogypsum were dried by placing them in an oven at 60°C for 24 hours. This was done to get rid of any moisture which might cause the hydration or reaction starting prematurely. The three types of stabilizers were kept separately in their sealed bags so that they don't lose their reactivity before mixing. The right amounts of soil, OPC, copper slag, and phosphogypsum for each mix proportion were weighed precisely with the help of a balance that shows the weight to the smallest unit. Combusting the constituent materials was first done thoroughly to get a homogeneous mixture during which the stabilizers were uniformly distributed throughout the soil mass. Calculated quantities of distilled water, which were fixed by referring to the Optimum Moisture Content (OMC) of each mix as derived from the Standard Proctor compaction test, were then taken in small amounts and mixed till a consistent, workable mix was obtained. The made mixes were filled in moulds at their corresponding OMC and Maximum Dry Density (MDD) values, according to the Standard Proctor procedure. Those specimens which were intended for longer time intervals of curing were after compaction put in a curing chamber that has controlled humidity and is maintained at a temperature of around 27 ± 2°C to avoid loss of moisture throughout the curing period. The testing at the curing periods of 7, 14, and 28 days was to capture the time-dependent changes of the stabilization.**Mix Proportions.**Based on the initial unconfined compressive strength (UCS) screening study results, the stabilizer content was decided. In the study, 1:1:1 mixture of Copper Slag, Phosphogypsum, and OPC was added to black cotton soil at a series of total admixture contents starting from 7.5% to 17.5% (at 2.5% intervals). Highest UCS was found at 12.5% by soil dry weight, which was taken as the optimum total admixture content. Then, at this fixed 12.5% dosage, different CS:PG:OPC compositions were tested and the 4:3:1 ratio resulted in the highest UCS value. Since the addition of admixture changes the soil-water interaction and the soil compaction properties, Standard Proctor tests were performed on the soil mixed with the 4:3:1 combination at various admixture contents to get proper OMC and MDD values for further testing. The subsequent changes are shown in Figures 5.

TESTS CONDUCTED

Atterberg Limits. Atterberg limit tests, which are composed of the Liquid Limit (LL), Plastic Limit (PL), and the resultant Plasticity Index (PI), have been carried out on both untreated and stabilized soil samples according to IS 2720 (Part 5): 1985. The liquid limit was measured by using the Casagrande percussion cup method, whereas the plastic limit was determined by the traditional thread-rolling technique. The samples were tested right after mixing without any curing time to get the immediate effect of stabilizer addition on the soil's plasticity traits. A decrease in the plasticity index after the addition of a stabilizer indicates a lower attraction of soil to water; this is a sign of cation exchange and the flocculation of clay particles.

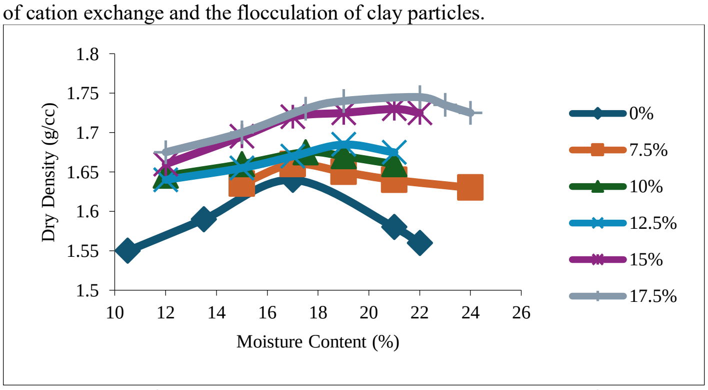

Figure 5 Variation of OMC with admixture content (CS:PG:OPC at fixed 4:3:1 ratio)

Swelling Test. The free swell index (FSI) of the untreated and treated soil samples was found according to IS 2720 (Part 40): 1977. In the procedure, 10 g of oven-dried soil that passed through a 425-micron sieve was taken separately in two graduated cylinders; one filled with distilled water and the other with kerosene. After the soils were left to come to an equilibrium for a period of 24 hours, the volume of swollen soil in water and the original volume of soil in kerosene were measured. The free swell index was determined as the percentage increase in the volume of soil in water compared to its volume in kerosene. Besides that, swell pressure tests were performed with the help of a fixed-ring consolidometer apparatus on compacted specimens that were prepared at OMC and MDD, as per IS 2720 (Part 41): 1977. For the test, the specimens were flooded with water, and the pressure which was needed to stop any volume change was monitored, thus giving the measure of the swelling capacity of the treated soil when it is confined.

Unconfined Compressive Strength (UCS) In order to assess the strength development of stabilized specimens during curing, Unconfined Compressive Strength Tests (UCS) were conducted as per IS 2720 (Part 10): 1991. Using static compaction at OMC and MDD, 38 mm diameter and 76 mm height cylindrical specimens were prepared, sealed, and cured for 7, 14, and 28 days. The specimens were loaded axially at the end of corresponding curing periods at a strain rate of 1.25 mm/min using a motorized loading frame until failure. Stress at failure was considered as the UCS. To reduce the variability of the experiments, a minimum of three specimens were tested for each mix proportion and curing period and their average values were taken.

RESULTS AND DISCUSSION

Atterberg Limits. Atterberg limits unveil fundamental aspects of soil plasticity, they are also very much linked to the engineering properties of fine-grained soils. Fig. 6 shows how the ternary stabilizer mixture changes the Liquid Limit (LL), Plasticity Index (PI), and Shrinkage Limit (SL) of black cotton soil. A regular decrease in the liquid limit and plasticity index was coupled with a gradual increase in the shrinkage limit for all treated samples as the stabilizer dosage was increased. Black cotton soil without any treatment had a liquid limit of 68%, plasticity index of 44.5%, and shrinkage limit of 12%, respectively, pointing to a severely expansive and plastic soil. When the stabilizer was added at 7.5% level, the LL was reduced to 47% and PI to 27%, which are approximately 31% and 39% reductions respectively, whereas the SL was 21%. At 10% of the stabilizer, the LL went down to 40.5%, PI dropped to 20%, and SL increased to 24%. The same pattern was going on quite smoothly through 12.5% (LL = 35%, PI = 16%, SL = 29%) and 15% (LL = 33.5%, PI = 15.5%, SL = 35%) levels of the mix. At the highest level of 17.5%, the LL obtained a minimum value of 27.5% a total change of 59.6% from the untreated soil whilst PI decreased to 12.5%, a change of almost 72%, and SL increased to 40%, a change of 233% over the natural soil value. The major cause of the liquid limit reduction is that ion-exchange reactions between the soil and the stabilizer are increasing; this is only one of the impacts of the compound. The calcium ions, which are the product of the hydration process of OPC and the dissociation of phosphogypsum, replace the monovalent and lower-valence cations adsorbed on the clay platelet surfaces. Such substitutions cause the diffused double layer around clay particles to shrink, reduce the clay particles' ability to hold water, and lead to their sticking together and forming larger clusters. Cementitious substances such as Calcium Silicate Hydrate (C-S-H) and Calcium Aluminate Hydrate (C-A-H) generated from the pozzolanic reaction of cement, copper slag, and available calcium link the clay aggregates together, and the hardening of the soil matrix results in a lowered water-absorbing capacity. The production of ettringite through the interaction of calcium aluminate hydrate with sulphate ions from phosphogypsum contributes to particle bonding stiffness, and hence the liquid limit decrease becomes more pronounced with the passage of curing time. The large increase in shrinkage limit from 12% to 40% over the dosage range signifies the gradual cementation and volume stabilization of the soil matrix, and thus a marked decrease in the shrink, swell potential, which is a characteristic of untreated black cotton soil.

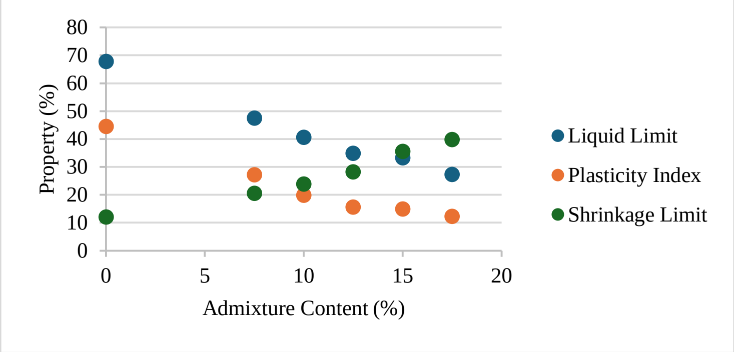

Figure 6 Variation of Atterberg's Limits with admixture content (CS:PG:OPC at fixed 4:3:1 ratio)

Swelling Behaviour. Figure 7 depicts the outcomes of free swell index (FSI) and swell pressure for the untreated, as well as stabilized, soil samples. Black cotton soil left untreated exhibited an extremely high free swell index of about 37%, which aligns well with the presence of montmorillonite mineral. Using the ternary blend brought about a drastic, notable and uniform decrease in both FSI and swell pressure across all the levels tested, and the decrease even became more pronounced with more stabilizer and longer curing time. At the moderate levels of admixture 10% and 12.5%, the FSI reduced to about 16% and 13%, respectively, which almost corresponded to a linear decrease. Swelling is curbed mainly by two, which also complement each other, mechanisms. The calcium from cement and phosphogypsum that enables the cation exchange, which is the first of these mechanisms, lowers the clay layers' electrochemical repulsion to such an extent that the diffused double layer contracts both limiting the inter-layer water adsorption that causes swelling. Besides, the conservation of water is limited furthermore by a decrease in the amount of water between the layers. In addition, the very slow formation of C-S-H, C-A-H, and ettringite phases not only occupy inter-particle voids but also enclose the clay particles in a rigid cementitious matrix that becomes a physical barrier to the volume increase when the soil is wetted. Phosphogypsum's function here is very important because the ettringite crystals formed in the pores act as micro-mechanical restraints against particle displacements due to swelling. At the optimum 17.5% ternary mix, the free swell index has been lowered to about 10%, which is almost 73% less than the original value of 37%, and swell pressure has been reduced to levels that are definitely subgrade soil quality compliant, thus verifying the proposed stabilizer system's ability to address the main engineering limitation of black cotton soil.

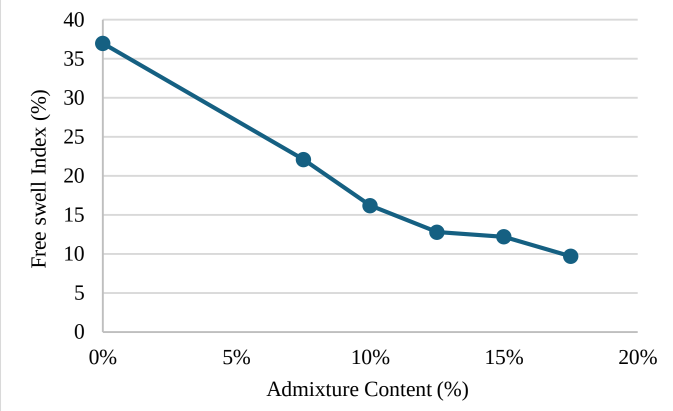

Figure 7 Variation of Free Swell Index with admixture content (CS:PG:OPC at fixed 4:3:1 ratio)

Unconfined Compressive Strength. Figure 8 gives us a visual representation of how the UBC of untreated and ternary stabilized samples varies with admixture content and curing period. The untreated black cotton soil that the authors used recorded a very low UCS of about 200 kPa, clearly illustrating the nature of the soil to be weak and highly compressible. Implementation of the ternary mixture not only led to a consistent increase in strengths of all the mix proportions but also the rise was quite significant at the different strength levels ranging from around 400-600 kPa at 7 days to 600-950 kPa at 60 days depending on admixture content. The strength that was initially observed was mainly due to the hydration of the OPC that was fast which led to the production of the C-S-H and C-A-H gels that in turn bound the soil particles and filled compacted voids. Upon further curing, the calcium hydroxide that was freed and the silica and alumina in the copper slag which was very active led to the formation of secondary pozzolanic reactions which is the reason for the production of additional cementitious compounds that go on to densify the soil matrix further The action of phosphogypsum in aluminate is through the formation of ettringite and it also has the ability to maintain the secondary reactions for longer periods of curing. The maximum UCS value of about 950 kPa was obtained at 12.5% admixture content after 60 days of curing, beyond which the 15% and 17.5% mixes showed decline in strength, implying that excess copper slag along with a non-proportional increase in activating binder leads to dilution of cementation efficiency. In summary, the best mixture gave a UCS increase of nearly 375% compared to the untreated soil which was a clear demonstration of the efficacy of the ternary stabilization system.

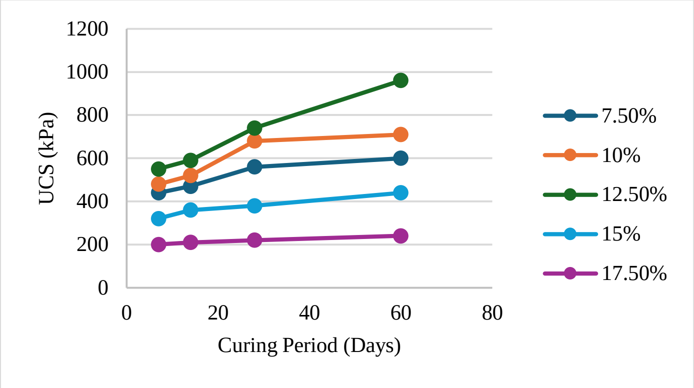

Figure 7 Variation of Free Swell Index with admixture content (CS:PG:OPC at fixed 4:3:1 ratio)

Conclusions

The conclusions were based on the results of Atterberg limits, free swell index, swell pressure, UCS and CBR tests along with supporting XRD and SEM analyses:

- The unmodified soil was very expansive with a liquid limit of 68% and plasticity index of 44.5% as well as shrinkage limit of 12%. At the ternary mixture of 17.5%, LL and PI were quite low whereas SL was very high!
- The free swell index decreased drastically from approximately 37% to 10% at the optimal mixture, the swell pressure was significantly lower too. This was achieved through cementation of pozzolans filling of pores and limiting clay expansion.
- UCS went up from about 200 kPa in the untreated soil to nearly 950 kPa at 12.5% admixture content after 60 days of curing which means a significant strength improvement has been made. The reason for the increase is attributed to progressive pozzolanic and sulfate-activated reactions while excess admixture content resulted in a slight decrease in cementation efficiency.

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