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Cyclic Behaviour of Black Cotton Soil Stabilized with a Ternary Blend of Ordinary Portland cement, Copper Slag, and Phosphogypsum

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Abstract
Black cotton soils are notoriously difficult to work with in road construction. Because they swell easily and lose strength under the weight of traffic, they often lead to pavement failure. In this study, we explored a more resilient solution: stabilizing the soil with a three-part blend of Ordinary Portland Cement (OPC), Copper Slag (CS), and Phosphogypsum (PG). By putting these mixtures through a series of 'stress tests' that simulate repeated traffic loading, we found that the ternary blend significantly stiffens the soil. While untreated soil tends to degrade quickly under pressure, our stabilized specimens held their ground much better. This durability comes down to the cementation products such as calcium silicate hydrate and ettringite that forms during the curing process. Ultimately, this mix not only met the strict stiffness standards required for modern road design but also offers a more sustainable way to build on challenging terrain. In addition, the stabilized soil showed improved resistance to deformation and maintained its strength even after repeated loading cycles. The combined action of OPC, CS, and PG created a denser soil structure, reducing the harmful effects of swelling and shrinkage. These findings highlight the potential of industrial by-products in developing cost-effective and environmentally friendly pavement subgrade stabilization techniques.
Keywords: Black cotton soil; Cyclic triaxial test; Secant shear modulus; Damping ratio; Copper slag; Phosphogypsum;

Introduction

Expand soils, which are also called black cotton soils on the Indian subcontinent, are actually the top of the list for most troublesome soil materials that civil engineers come across. These soils, which occur very largely in the Deccan Plateau and a number of semi-arid areas of India, have such a high content of montmorillonite mineral that they swell enormously when wetted and shrink a lot when dried. The resultant volumetric changes lead to differential settlement, longitudinal cracking, and early deterioration of road pavements, especially at the subgrade level where moisture changes are most intense which was also evidenced by Puppala et al. (2021). On top of the problems of high plasticity and low bearing capacity of the soil near the surface, the reaction of expansive subgrade soils to repeated dynamic loading i.e. due to traffic is a matter of great concern to an engineer. This is because the build-up of plastic strains and the continuous loss of stiffness, under cyclic stresses, may cause fatigue failure and the gradual breakdown of flexible pavements over time (Cai et al., 2020).

Subgrade soils' dynamic properties such as shear modulus, damping ratio, and resilient modulus dictate how well a pavement can handle and absorb traffic stresses without getting damaged. The drop in stiffness after repeated loadings is primarily caused by the generation of excess pore water pressure, particle movement, and bond breakage at inter-particle contacts, which are further intensified in expansive clays due to their weak and moisture-sensitive nature (Yang et al., 2020). Hence, it is of utmost importance that any stabilization method used for expansive subgrade soils should be tested not only for static strength and ability to reduce swelling but also for potential to improve and maintain dynamic stiffness during continuous loading.One of the most classic and highly effective techniques in the area of soil stabilization for the improvement of expansive soils has been chemical stabilization with the help of cementitious and pozzolanic binders. Lime and Ordinary Portland Cement are, by far, the leading two materials as stabilizers in the world today, and their capability is based on the calcium silicate hydrate and calcium aluminate hydrate gels which are created by hydration and secondary pozzolanic reactions and, over time, cement the soil particles together to produce a cohesive low-plasticity mass (Consoli et al., 2021.). Nevertheless, the environmental impact of cement production, which accounts for about 8% of global CO2 emissions and the increasing price of conventional stabilizers have caused more and more people to be interested in partial or even full replacement of these materials with industrial by-products which have the same or even complementary reactivity.) (Latifi et al., 2020).

Besides other industrial by-products, copper slag and phosphogypsum have shown excellent potential for soil stabilization. Copper slag, a waste from copper smelting, is produced at the rate of 2.2 to 3 tonnes per tonne of refined copper which is rich in amorphous silica, alumina, and iron oxide making it into a latent pozzolanic material that can be activated with alkali when calcium hydroxide is released during cement hydration (Najjar et al., 2021). Phosphogypsum, a calcium sulfate dihydrate residue from phosphoric acid manufacturing, is a source of sulfate ions which upon reacting with calcium aluminate hydrate phases result in the formation of ettringite which is a stable compound that helps to reduce the pore size of the stabilized soil and control the swelling by physically restricting the expansion of clay particles (Jiang et al., 2021). The complementary chemical roles of these two by-products, when combined with OPC in a ternary system, create a synergistic stabilization environment that has demonstrated superior static engineering performance in recent research. But, the impact on the dynamic behavior of soils treated with these ternary blends is still largely missing from the literature.Numerous researchers explored dynamic behavior of natural and stabilized very fine soils subjected to cyclic loading. Vucetic and Dobry (1991) laid down the basis for the relationship between the normalized shear modulus reduction and damping ratio to the cyclic shear strain amplitude and plasticity index. They showed that soils with higher plasticity tend to lose stiffness more when subjected to the same strain level. Later studies focused on stabilized soils as well. Chae and Au (1974) observed that lime-salt treatment of expansive soil not only prevented swelling and increased strength but also resulted in higher dynamic shear modulus and lower damping ratio. They thus showed that cementation compounds formed during stabilization are mainly responsible for changing the energy dissipation mechanism of treated soil.

In their study, Saride and Dutta (2016) found that fly ash stabilization of expansive clays gradually led to an increase in shear modulus and a decrease in damping ratio as the fly ash content and curing period were increased. They argued that these changes arose from the formation of pozzolanic cementitious products that stiffened the inter-particle bond network. Using strain-controlled cyclic triaxial tests, Ashango and Patra (2016) studied the behavior of expansive soil treated with a ternary combination of steel slag, rice husk ash, and quicklime. Their results showed that cyclic stiffness of the soil improved by as much as 78%. Based on this finding, they recommended the treated soil as a subgrade material. Li et al. (2018) studied the dynamic properties of steel slag-sand mixtures and showed that both the high angularity and pozzolanic reactivity of steel slag contributed to the enhancement of secant shear modulus and decrease in damping ratio with regard to natural sand mixtures. For their part, Golpazir et al. (2016) went a step further by studying the dynamic properties of polyurethane-sand composites. They presented cyclic triaxial testing as a powerful tool to measure the dynamic properties of non-conventional stabilized geomaterials.

For instance, in discussing the effects of loading cycles on dynamic properties, Shafiee and Ghate (2008) indicated that the damping ratio does not vary much with the number of loading cycles in cementitiously stabilized soils. Similarly, Takele et al. (2017) who revealed that damping ratio decreases slightly with the progress of cycling in stabilized specimens due to the cementation bonds which inhibit the slipping of particles between each other confirmed the finding of the former. The effect of strain amplitude on the dynamic properties was, in fact, the most clearly demonstrated: an increase in strain amplitude lowers the shear modulus due to particle reorientation and pore pressure generation while the damping ratio is enhanced through increased frictional energy dissipation in each cycle. Subramaniam and Banerjee (2013), Mojezi et al. (2020) have also expressed similar views. Resilient modulus, or the ratio of repeated deviator stress to the recoverable axial strain after many loading cycles, has been recognized as the most important parameter of unbounded material properties in mechanistic pavement design procedures (Christopher et al., 2006). Its measurement by repeated load triaxial testing at different stress levels allows the direct evaluation of subgrade stiffness under actual traffic load conditions. Mamata and Dinesh (2017) in their work on lime-stabilized weak subgrade and Wei et al. (2018) on oil shale ash and fly ash-modified silty clay have shown an almost linear increase in the curved of resilient modulus with the amount of stabilizer and the length of curing, through which the authors confirmed that pozzolanic and cementitious reactions underpin the recovery of elastic stiffness on reloading.

Research Gap and Objectives

One of the main reasons why the proposed work is important is because, a large amount of evidence supporting the static geotechnical benefits of OPC, Copper Slag, Phosphogypsum ternary stabilization for expansive soils have been accumulated. However, no paper has yet been published that studies the dynamic behavior of the soils treated with this specific combination. In a cement-activated matrix, the formation of ettringite due to phosphogypsum and the pozzolanic reactivity of copper slag give a very different microstructure whose effect on cyclic stiffness, energy dissipation, and resilient response under repeated loading is not known yet. Also, the effect of ternary admixture content and curing period on how quickly and in what way shear modulus is degradation with loading cycles and strain amplitude is still not known for this system.

The present paper, thus, seeks to fill this research gap by focusing on these specific points:

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(i) To measure the secant shear modulus and damping ratio of black cotton soil treated with different proportions of OPC-CS-PG ternary blend under strain-controlled cyclic triaxial loading at multiple strain amplitudes and over 100 loading cycles.
(ii)To study how admixture content and the curing period affect the dynamic stiffness and energy dissipation properties of the stabilized soil.
(iii)To find the resilient modulus of the stabilized soil under the simulated subgrade stress states and to evaluate its capability for flexible pavement design purposes.
(iv) To link the presented dynamic characteristics to the microstructural and mineralogical changes resulting from the ternary stabilization reactions.

MATERIALS USED

This part outlines the physical, chemical and index traits of three distinct materials that were the main focus of the stabilization study: black cotton soil; copper slag; and two types of cementing material Ordinary Portland Cement and Phosphogypsum (PG).

Black Cotton Soil. The swelling soil that bared the experiment was a black cotton soil, a montmorillonite majorly component. Montmorillonite is an expansible clay mineral. A combination of routine laboratory tests was performed to determine the physical and index properties of soil samples. The results are presented in Table 1. The Table 2 shows the elemental oxide composition of the soil. A scanning electron microscopy (SEM) was done to learn about the micro-level structure of the particles. It from Fig. 1 can be seen that the soil is arranged in a very loose way having large inter-particle voids. Weak Van der Waals forces together with the presence of cations which hardly compensate the charge deficiency of clay platelets are responsible for this type of arrangement. Such weak bonding between particles makes the soil very vulnerable to the entry of moisture. Moisture causes volume change i.e. swelling of the soil which is a characteristic of this type of soil.

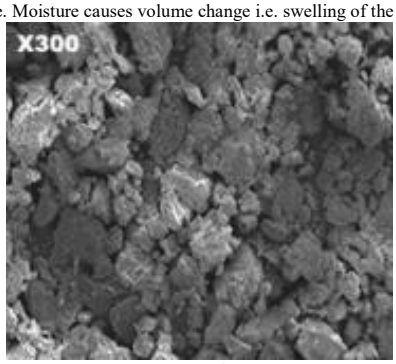

Figure 1 SEM Image of Black Cotton Soil

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. Copper slag, a by-product in the refining of copper, is basically a dense, dark, glassy, granule-like material. Table 1 mainly attributes its surprisingly high specific gravity of 3.68 to the presence of iron since iron-containing compounds besides that unit weights are much higher than most other mineral components. Copper slag grain size distribution is medium-sized sand level. Chemical composition of the oxides is shown in Table 2, where the main constituents are SiO_2, Al_2O_3, Fe_2O_3, and CaO. There were no sulfates in the slag, which chemically it is very stable, with no risk of super-expansion due to sulfate. The collective percentage of silica, alumina, and iron oxide goes beyond 87%, which is above 70%, and that is an indication for materials that will produce effective pozzolanic compounds in accordance with 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, a property that produces high inter-particle friction and soil shear resistance.

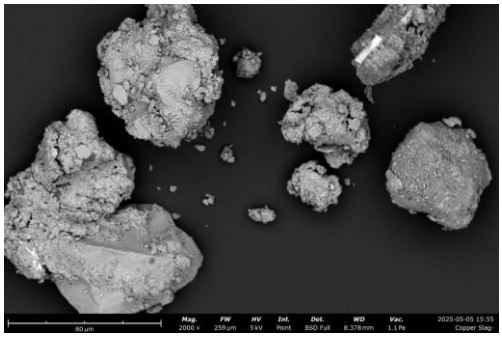

Figure 2 SEM Image of Copper Slag

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Phosphogypsum (PG) Phosphogypsum is a form of industrial waste, very high in sulfate, resulting from the creation of phosphoric acid through the conversion of phosphate rock by the wet process. Chemically, it is mostly calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$) with a few leftover phosphates, fluorides, and other minor impurities as shown by its chemical composition in Table 2. Phosphogypsum, when it comes to soil stabilization, behaves quite differently and even complements the function of other chemicals. Adequate absorption of sulfate ions by phosphogypsum causes it to chemically interact with calcium aluminate hydrates, the source of which was the hydration of cement, resulting in the formation of ettringite ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$) a stable, needle-shaped crystalline phase. As ettringite grows and fills the network of soil pores, it reduces the void ratio and enhances the particle bonding that ultimately results in lesser swelling and more load-bearing capacity. On top of that, the calcium of phosphogypsum can be used to generate an additional activating medium which will expose the latent pozzolanic property of copper slag. Certain physical characteristics of phosphogypsum such as specific gravity and particle size are shown in Table 1. Also, the SEM image of phosphogypsum of Fig. 3, shows its characteristic platy to tabular crystal morphology which is consistent with gypsum mineral habit.

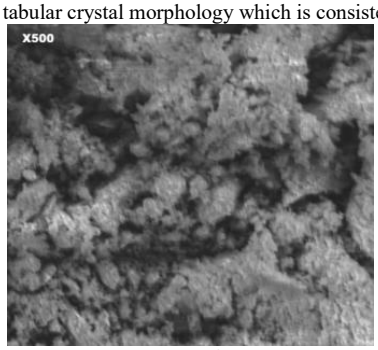

Figure 3 SEM Image of Phosphogypsum

Ordinary Portland Cement (OPC) 43-grade Ordinary Portland Cement conforming to IS 8112 was the main binder in the present study. Details of chemical composition of the OPC used are given in Table 2. The choice of cement was motivated by the fact that it is a quick starter in hydration reactions after coming into contact with water and therefore causes release of calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) gels apart from free calcium hydroxide ($Ca(OH)_2$). The released portlandite has dual roles: on the one hand, it is directly involved in early strength development through cementitious bonding, and on the other hand, it acts as an alkali activator which induces secondary pozzolanic reaction of the copper slag with silica and alumina. Finally, the strengthening of the soil framework occurs gradually as a result of cementitious reaction products filling the voids between particles. The physical properties of OPC like specific gravity and fineness are presented in Table 1.Therefore, the four materials in total actually perform the function by complementing each other: cement provides the main structure of the binder and the alkaline activation environment, copper slag delivers additional pozzolanic phases, and phosphogypsum promotes ettringite formation while at the same time it increases sulfate-activation of slag. All in all, these are the key elements of the ternary stabilization system forming the basis of the current research.

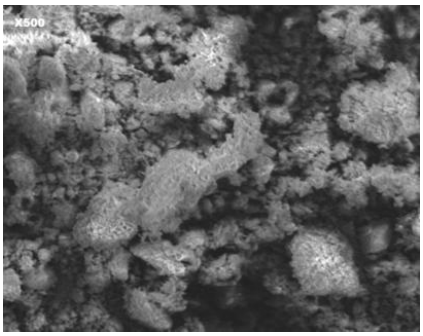

Figure 4 SEM Image of OPC

EXPERIMENTAL PROGRAM

Sample Preparation. Black cotton soil that was taken from the field was air-dried in the lab and then smashed with a rubber mallet to separate clumps of soil before it was sifted through a 4.75 mm IS sieve for consistency among specimens. The prepared soils were placed in air-tight containers to protect from accidental moisture uptake before the tests. Copper slag, being a granular, free-flowing material, was directly obtained from a copper smelting plant and did not require any further processing. Cement and Phosphogypsum were dried in an oven at 60°C for 24 hours to remove the moisture and to prevent their premature hydration. All the stabilizing materials were kept separately in sealed bags until the time of mxing. At first, the indicated quantities of soil, OPC, copper slag, and phosphogypsum were weighed with a precise balance for each mix proportion, and the dry-mixing was done very well to get the even distribution of stabilizers in the soil mass. The distilled water which was equal to the Optimum Moisture Content (OMC) of each mix was found by the Standard Proctor compaction test, and this water was added bit by bit and mixed until a uniform mixture was obtained. Cylindrical specimens (38 mm diameter and 76 mm height) were compacted statically at the respective OMC and Maximum Dry Density (MDD) values. The ones being kept for further curing were wrapped with cling film and put in a humidity-controlled chamber (was at 27 ± 2°C). The assessment of dynamical properties was done at the time of 7 and 28 days curing.

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.

DYNAMIC PROPERTIES OF TERNARY STABILIZED BLACK COTTON SOIL

Cyclic Triaxial Testing Procedure. Based on the initial UCS screening, a 1:1:1 mixture of Copper Slag, Phosphogypsum, and OPC was added to black cotton soil at total admixture contents ranging from 7.5% to 17.5% at 2.5% intervals. The highest UCS was recorded at 12.5% by soil dry weight, which was adopted as the optimum total admixture content. Subsequently, different CS:PG:OPC compositions were tested at this fixed 12.5% dosage, and the 4:3:1 ratio yielded the highest UCS value. Since the addition of admixture alters soil-water interaction and compaction behaviour, Standard Proctor tests were performed on soil mixed with the 4:3:1 combination at various admixture contents to determine the appropriate OMC and MDD values for subsequent testing, with results shown in Figure 5.

Strain-controlled cyclic triaxial experiments were carried out on untreated and ternary-stabilized black cotton soil. These tests followed the standard ASTM D3999 (ASTM, 2003) to assess the effect of the OPC, Copper Slag, Phosphogypsum blend on the soil dynamic features, which are the secant shear modulus and the damping ratio. Cylindrical samples of 38 mm diameter and 76 mm height were made at optimum moisture content and maximum dry density corresponding to each mixing proportion level. A submersible load cell of 50 kN capacity was used for recording the load response during the cyclic loading. Before cyclic load application, all specimens were subjected to isotropic consolidation under a confining pressure of 250 kPa. Undrained cyclic loading was applied sinusoidally at a frequency of 0.5 Hz, with 100 loading cycles produced at three shear strain amplitudes of 0.5%, 0.7%, and 1.0%. Dynamic properties were computed from the hysteresis loop of the first loading cycle. The secant shear modulus was obtained from the slope connecting the peak compressive and tensile stress-strain points,

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while the damping ratio was derived from the ratio of the enclosed loop area to the inscribed triangle area. Cyclic behaviour was assessed on untreated soil and soil treated with admixture contents of 7.5%, 12.5%, and 17.5% at the fixed 4:3:1 CS:PG:OPC ratio, cured for 7 and 28 days, to evaluate the combined effect of admixture content and curing time on dynamic properties.

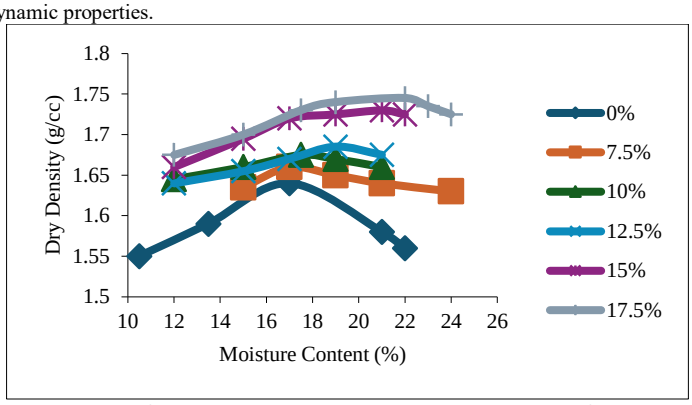

Figure 5 Variation of OMC with admixture content (CS:PG:OPC at fixed 4:3:1 ratio)

EFFECT OF LOADING CYCLES

Secant Shear Modulus. Fig. 6 reveals how the secant shear modulus changed over a number of loading cycles for untreated and ternary stabilized soils after 28 days of curing. Initially, the modulus of the untreated black cotton soil was about 20.1 MPa, and it gradually dropped to 15.7 MPa at cycle 100, resulting in a reduction of 22%. The decrease was mainly caused by the buildup of pore water pressure and damage to the clay fabric during the cyclic loading at a constant volume condition. On the other hand, the stabilized samples were less affected by the test showing higher initial moduli and smaller degradation. A 7.5% mix saw Gsec decrease from around 28.5 MPa to 23.2 MPa after 100 cycles, which was a 19% decrease. The 12.5% mix had an initial Gsec of about 30.1 MPa, which was lowered to 27.2 MPa by the 100th cycle, a degradation of only about 10%, a result that is consistent with the denser cementitious matrix formed at the higher stabilizer dosage. The 17.5% combination started with the highest initial Gsec of about 32.8 MPa, ending at about 25.5 MPa by cycle 100. The modifications seen in each of the stabilized samples were largest in the first 50 cycles, and after that the rate of weakening was so low that it was almost invisible, which shows that the greater C-S-H, C-A-H, and ettringite cementitious "bridges" were strong enough to be resistant to further deterioration.

The gradual increase in cyclic stiffness that was observed when more admixture was added and when the specimens were given more time to cure demonstrates that the pozzolanic reaction maturity is indeed playing a key role in the dynamic behavior of stabilized black cotton soil.

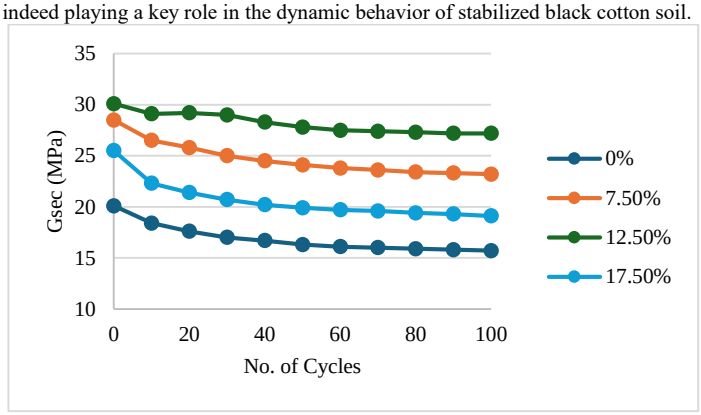

Figure 6 Variation of Secant Shear Modulus with admixture content (CS:PG:OPC at fixed 4:3:1 ratio)

Damping Ratio. The fig 7 shows the variation of the damping ratio through the load cycles. The untreated black cotton soil had the highest damping ratio all through, approximately 25% at cycle 1 and gradually going down to about 20% by cycle 100, thus indicating its vulnerability to particle rearrangement and pore pressure increase during cyclic loading. On the other hand, all the ternary stabilized specimens showed lower damping ratios all the time which went down gradually as the load cycles increased. At 7.5% admixture level, the damping ratio dropped from about 15% at cycle 1 to nearly 11% at cycle 100. A 12.5% mixture showed a reduction beyond, beginning at 10% and remaining at around 8% at cycle 100. The 17.5% admixture level showed the smallest damping ratio among the stabilized specimens, falling from nearly 12% at cycle 1 to about 7.5% at cycle 100.

Initially, one might think that material softening due to continuing cycles should raise the energy dissipation capacity, but the downward trend in damping ratio verifies the literature results on cemented soils, where cementitious compounds gradually restrict the inter-particle frictional slippage, which is the main energy dissipation source during cyclic loading. For the ternary stabilized system, the intertwined network of C-S-H, C-A-H, and ettringite crystals hinders the relative particle displacement even as the stiffness decreases slightly, thereby reducing the energy dissipated per cycle. Besides, the generation of suction in the unsaturated zones of compacted cured specimens probably had a role in the further reduction of damping ratio with successive cycles. The cumulative diminution in damping ratio with the increase of admixture content and curing time clearly indicates the progressive stiffening of the soil matrix through pozzolanic cementation.

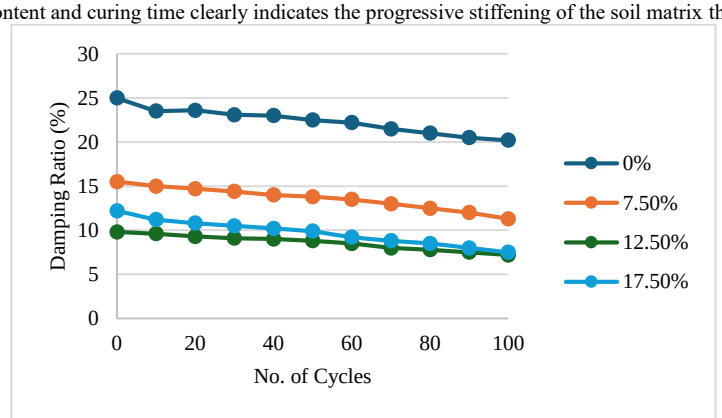

Figure 7 Variation of Damping Ratio with admixture content (CS:PG:OPC at fixed 4:3:1 ratio)

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Effect of Admixture Content

The effect of ternary admixture dosage on dynamic properties was analyzed by comparing the untreated soil with those prepared at admixture levels of 7.5%, 12.5%, and 17.5%, respectively, under the same conditions of strain amplitude and frequency. Figures 6 and 7 p. show that admixture content is strongly and positively related to secant shear modulus, whereas it is negatively related to damping ratio.

Fig. 6 shows that the untreated soil had an initial Gsec of about 20.1 MPa and the value dropped to nearly 15.7 MPa at the 100th cycle. However, the Gsec at the 7.5% admixture was initially at the level of 28.5 MPa approximately, and 12.5% mixture was the top performer recording an initial Gsec of 30.1 MPa approximately, a value which became steady at approx. 27.2 MPa after 100 cycles, which is a drop of only about 10% as opposed to 22% for untreated soil. Gsec was initially at about 32.8 MPa with 17.5% mixture but it went down to around 25.5 MPa at the 100th cycle, indicating that besides the optimum 12.5% dosage, a higher copper slag amount without proportional increase in binder slightly reduces cementation efficiency. The increased shear modulus with admixture content is because of the larger amounts of C-S-H, C-A-H, and ettringite formed at high dosages which in turn makes the soil matrix denser and strengthens inter-particle bonds.

According to Fig. 7, the damping ratio behaved in a completely opposite way to admixture content. Untreated soil was at the top with the damping ratio gradually decreasing from 25% to 20% over the 100 cycles. When 7.5% admixture was introduced, the damping ratio reduced from near 15% down to 11%, whereas at 12.5% it was reduced from 10% down to 8%, and with 17.5% it was reduced from about 12% down to 7.5% at the 100th cycle. The gradual decrease in the damping ratio with admixture content not only displays as the dense cementitious network limits the inter-particle frictional slippage that the soil energy dissipation mechanism is shifted from friction-dominated to rigidity-dominated behaviour, but it also agrees with the general response of chemically stabilized fine-grained soils as documented in literature.

Conclusions

The present study investigated the changes in dynamic behavior of black cotton soil stabilized with a ternary mixture of Ordinary Portland Cement, Copper Slag, and Phosphogypsum through strain-controlled cyclic triaxial tests. Major conclusions based on the experimental work are as follows:

- Untreated black cotton soil experienced very fast and extreme modulus reduction due to shear, with the modulus dropping from around 20.1 MPa at cycle 1 to 15.7 MPa at cycle 100, which was almost a 22% decrease, mainly due to excess pore water pressure generation and breakdown of the delicate clay fabric in undrained cyclic loading condition.
- The modulus of rigidity determined at the midpoint of the stress-strain curve constantly improved along with mixing level and incubation period. At 28 days, the 12.5% mixture had the maximum initial Gsec value close to 30.1 MPa, and its decline after 100 cycles has been only around 10%, in contrast to 22% of untreated soil, which supports the enhanced capability of the cement matrix to resist cyclic stiffness deterioration. The 17.5% mixture experienced a slightly accelerated fall, revealing the reduction of the effectiveness of cementation beyond the optimal dose.
- The damping ratio showed a steady opposite trend with both the level of admixture and time of curing. Over 100 cycles, the untreated soil had a damping ratio ranging from 25% to 20%, whereas at 28 days, the 12.5% and 17.5% mixes were at their minimum, dropping to about 8% and 7.5% by cycle 100, respectively, indicating a gradual move from friction-based to rigidity-controlled energy dissipation mechanism.
- The reduction in dynamic characteristics of stabilized samples occurred in two stages, firstly with the highest drop being within the initial 50 cycles, then the stronger cementitious bonds formed by C-S-H, C-A-H, and ettringite were able to offer so much resistance to further structural damage that the degradation rate became almost zero near cycle 100.

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