

Experimental Investigation on the Geotechnical Properties of Clayey Soil Stabilized with Phosphogypsum and Nano Silica

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Abstract - The engineering performance of clayey soils is often limited by their high plasticity, low strength, excessive compressibility, and significant volume changes under varying moisture conditions. These characteristics can adversely affect the stability and service life of civil engineering structures. Soil stabilization has become an effective technique for improving the behavior of such soils, and the use of industrial by-products and nanomaterials has emerged as a sustainable and economical approach. In this context, phosphogypsum, a by-product of the fertilizer industry, and nano silica, a highly reactive material with excellent binding properties, have been selected as stabilizing agents. This research presents an experimental investigation on the geotechnical properties of clayey soil stabilized with phosphogypsum and nano silica. Phosphogypsum is incorporated at replacement levels of 15%, 20%, and 25% by the dry weight of soil, while nano silica is added at 1.0%, 1.5%, and 2.0%. An untreated clayey soil specimen is used as the reference material for evaluating the effectiveness of the stabilization process. A comprehensive laboratory testing program is carried out to examine the changes in the physical and mechanical properties of the stabilized soil. The investigation includes the determination of index properties, compaction characteristics, strength parameters, and bearing capacity using standard laboratory procedures. The test results are analyzed to identify the influence of different proportions of phosphogypsum and nano silica on the engineering performance of the soil and to determine the most effective combination of the two stabilizing materials. The study is expected to demonstrate that the combined application of phosphogypsum and nano silica can significantly improve the geotechnical characteristics of clayey soil by reducing plasticity, enhancing compaction behavior, increasing strength, and improving bearing capacity. In addition to improving soil performance, the utilization of phosphogypsum provides an environmentally responsible solution for the beneficial reuse of industrial waste, thereby supporting sustainable construction practices. The outcomes of this research are

anticipated to provide useful guidance for the application of alternative stabilizing materials in pavement foundations, embankments, and other geotechnical engineering projects.

Key Words: Compaction test, CBR, UCS, Phosphogypsum, Nano Silica

INTRODUCTION

Soils lose strength and exhibit significant swelling and shrinking characteristics when they come into touch with water. Expansive soils are what these are called. These soils display significant compressibility, excessive volume changes, and great sensitivity to variations in water content. Because this type of soil is so pliable, construction projects built on it may experience cracks and other damage.

Approximately 20% of India is made up of expanding soil, which includes nearly the whole Deccan Plateau. They are mostly black and reddish brown in hue and are typically found 0.5 to 10 meters below the surface. Because the expansive soil is prone to volume variations when it comes into contact with water from rain or capillary action from the water table, it will expand and could elevate the structures placed on top of it.

Therefore, these soils are unsuitable for construction until they are sufficiently stabilized, which may increase the expansive soils' low bearing capacity. Approximately 46% of India's total geographical area is covered with alluvial soil, which is the most important type of soil in the nation.

Clay, the main constituent of expansive soils and a very fine soil, makes up the majority of alluvial and black cotton soils. These soils have swelling tendencies and absorb a lot of water due to the cohesiveness of clay, which can produce problems including bulging, low soil bearing strength, and foundation fractures.

2. Literature Review

Shalaby et al. (2024)

This investigation aims to analyze and differentiate the effectiveness of nano-white cement in augmenting the mechanical traits of kaolin independently and alongside nano-silica. According to the compaction test findings, the maximum dry density, plasticity index, and workability of kaolin soil modified with various amounts of nano-white cement diminished. The perfect moisture content, plastic limit, liquid limit, and unconfined compressive strength were all augmented. The studied samples, treated only with 0.9% nano-silica, achieved their optimal strength qualities before seeing a decline. When juxtaposed with the results from the sample receiving the maximum percentage of nano-white cement alone, the samples incorporating the minimal percentage of nano-silica alongside different proportions of nano-white cement shown enhanced readings in unconfined compressive strength. In addition, the SEM photographs of the treated specimens represented the physical and chemical relationships between soil particles, nano-white cement, and nano-silica.

Jijo James et al. (2023) Phosphogypsum (PG), an industrial waste product, was added to lime in the study to stabilize the soil. For soil stabilization, three lime dosages were used: initial consumption of lime (ICL), optimal lime content (OLC), and less than ICL (LICL). The study examined the stress-strain properties of soil composites stabilized with these three lime contents and adjusted with the best PG dosages. The wasted samples used for a series of unconfined compression strength tests with different combinations of lime and optimal PG content underwent mineralogical investigations. An early strength gain of 8.8%, 14.1%, and 13.9% and a delayed strength gain of 9.9%, 19%, and 19.7% for 3%, 5.5%, and 7% for the lime-stabilized soil, respectively, were obtained by adding an optimal dosage of PG. Because PG amended the stabilizing reactions, it was discovered that adding PG to the lime increased its stiffness, residual strength, and decreased its brittleness. However, appropriate PG alteration of ICL rather than OLC yielded the most positive result in terms of the overall improvement of soil attributes. The results obtained from stress-strain characteristics were also corroborated by microanalysis of the X-ray diffraction scatter. When compared to the other two, ICL with its ideal PG dosage demonstrated a better progression of pozzolanic reactions in terms of an increase in CSH peaks and a decrease in soil mineral peaks.

Wadhonkar et al. (2022) In order to enhance the qualities of black cotton soil, numerous experimental investigations have been conducted recently. There is a lot of black cotton soil in most parts of India, which makes civil structures difficult to maintain. In the absence of moisture, this soil primarily shrinks, and when moisture is present, it swells, which could cause engineering constructions that depend on it to fail. Research of several prior research indicates that the incorporation of admixtures such as fly ash, rice husk ash, GGBS, WMP, and WCP can enhance the geotechnical properties of black cotton soil. The rapid industrialization of today results in problems such as environmental pollution and the management of industrial waste. This evaluation emphasizes the use of industrial materials. There is a lot of potential for using industrial waste and other waste materials to stabilize expansive soils, according to a thorough analysis.

Bhavsar et al. (2022) - The most crucial element in building any kind of structure is the soil's engineering qualities. Black cotton soil covers 51.8 million hectares of land in India. Because this expansive soil can expand or contract in response to seasonal variations in moisture content, it can pose a significant risk to engineering projects. However, thermal power sectors produce millions of tons of fly ash, a waste product. "How to utilize the industrial waste product" is currently a big issue. This analysis explores how increasing percentages of fly ash (0%, 10%, 20%, and 30%) influence the geotechnical parameters (liquid limit, plastic limit, plasticity index, maximum dry density, and optimum moisture content) of expansive soil.

Pawar et al. (2022) the employment of steel slag in soil stabilization is a recent innovation. The main goal of this investigation is to assess the effect of steel slag on the strength properties of clayey soil. Steel slag is mixed with clayey soil in ratios of 10%, 15%, 20%, 25%, and 30% according to dry weight. Our investigation identified the optimal steel slag content by analyzing the highest unconfined compressive strength. A number of subsequent laboratory analyzes have been executed on this optimal blend to determine its viability as a stabilizer. The examination was additionally executed with typical stabilizing components like 10% fly ash and 5% cement in combination with clayey soil, leading to the ascertainment of the most suitable blend. Thereafter, the findings are contrasted appropriately.

Guoping Qian et al. (2022) Phosphogypsum (PG), a secondary product arising from the synthesis of phosphoric acid, confronts issues associated with its large annual generation and complicated disposal processes. There exists a significant demand for fillers in road paving, which could provide as an efficient means for leveraging PG resources. The research began by establishing three ratios of the phosphogypsum–lime–fly ash (PLF) composite, based on orthogonal experimental methods. The overall performance of the PLF combination was examined using the compression rebound modulus test, unconfined compressive strength test, flexural tensile strength test, dry shrinkage test, and temperature shrinkage test, respectively. The evidence reveals that the inclusion of crushed stone in the PLF mixture can greatly augment the compression rebound modulus, unconfined compressive strength, and flexural tensile strength. The amplified concentration of PG within the composite can bolster the dry shrinkage and thermal shrinkage attributes of the blend. The ideal ratio of the PLF mixture is suggested based on the road layer specifications, which might enhance road construction and PG resources.

J. James et al. (2021) This research examines the feasibility of a composite binder created from two industrial solid byproducts, namely phosphogypsum and fly ash, in conjunction with lime. Three varying ratios of phosphogypsum and fly ash were investigated, and the essential minimum lime levels for activation were identified by the Eades and Grim pH analysis. The amalgamations of lime, fly ash, and phosphogypsum were subsequently cast into cubes, using both their paste and mortar variants, blended with sand in a 1:3 ratio. They underwent a curing process for seven days, after which their compressive strength was assessed. Standard Portland cement and lime mortar blocks were also produced as control specimens for the purpose of comparative strength assessment. The research indicated that a 5% lime combination with fly ash and phosphogypsum at a 3:1 ratio yielded the highest strength in the cubes. The advanced lime–fly ash–phosphogypsum composite mortar showed better strength relative to standard Portland cement and lime mortar. The perfect blend of lime, fly ash, and phosphogypsum in mortar masonry prisms showcased strength similar to that of Portland cement mortar masonry.

Anusha H M et al (2021) Expansive soils refer to soils that create considerable issues when they experience changes in moisture content. Phosphogypsum serves as an industrial waste by-product that may be used for

stabilizing soil. The study assesses the efficacy of lime-stabilized soil with Phosphogypsum at initial, 7, and 14 days of curing compared to the strength of black cotton soil enhanced with Phosphogypsum during the same periods. The unconfined compressive strength test indicates that a 6% concentration of Phosphogypsum is ideal, producing the maximum soil strength when utilized independently. The integration of 3% lime and 6% Phosphogypsum results in optimal strength, which is significantly greater than that of black cotton soil treated exclusively with Phosphogypsum.

Dhanasekar et al (2021) Expansive soils pose significant challenges for civil engineers. In order to attain the requisite characteristics of soil for construction, it is essential to improve these black cotton soils to fulfill their specifications. Numerous treatment techniques exist to alter the characteristics of black cotton soils. Stabilizing the soil improves its qualities, rendering it appropriate for subgrade construction. This analysis explored the interactive influence of Lime and Phosphogypsum (PG) on the compaction attributes, Atterberg's Limit, Unconfined Compressive Strength (UCS) of local soil, California Bearing Ratio (CBR), and direct shear test of black cotton soil with varying amounts of Lime and Phosphogypsum. The research implies that black cotton soil modified with Lime and Phosphogypsum at a (4:4) ratio shows improved strength attributes. Therefore, one can conclude that Lime and Phosphogypsum are effective for stabilizing black cotton soils meant for pavement subgrade.

Sabhnani et al (2021)

This article analyzes the stabilization outcomes from diverse study undertaken by different scholars, which aids in evaluating the potential of industrial byproducts for the stabilization of clay-rich soil. This review manuscript evaluates studies about the use of phosphogypsum and surkhi, waste products from various industries, in soil stabilization efforts. The synthesis of phosphoric fertilizer produces phosphogypsum as a secondary product, whereas surkhi, referred to as brick kiln dust, is a byproduct of fire clay brick production. The soil enhanced by these wastes produced by industries significantly influences the clay-rich soil. In addition, this soil stabilization approach is both exceptionally eco-conscious and financially efficient, while also repurposing industrial byproducts more effectively.

P. Kulanthaivel et al (2021)

This study explores a laboratory examination aimed at augmenting the shear strength and compaction traits of problematic clayey soil by utilizing nano-silica (0.2, 0.4, 0.8, and 1.0%) and polypropylene fiber (0.25, 0.50, 0.75, and 1.0%). The diameter of the nanoparticles utilized in this study was determined to range from 10 to 20 nm according to the Transmission Electron Microscopy (TEM) analysis.

Nair et al. (2020)

A strategy to reach the aim involves adjusting the mechanical traits of the soil using methods termed soil enhancement techniques. Nano silica is added to the soil samples in distinct ratios, namely 0.2%, 0.4%, 0.6%, and 0.8%. The compaction test serves to identify the maximum dry density (MDD) and ideal moisture content (OMC) for kaolinite soil. The strength attributes of clayey soil are determined by unconfined compressive strength. Higher ratios caused a lower plasticity index as a result of an increase in the plastic limit and a decrease in the liquid limit.

Safi et al. (2020)

Expansive soil is incapable of meeting all engineering requirements and cannot support the load transmitted by the foundation to the ground. Soil must possess high quality and substantial bearing capacity, exhibit excellent compressibility and durability against water, and minimize its permeability factor. Various waste materials utilized for the stabilization of expanding clay soil originate from four primary sources: industrial, agricultural, mineral, and home waste. This category of stabilizing methods is both cost-effective and utilizes readily available waste materials.

Singh et al. (2019)

The major aim of this investigation is to identify the most effective approach to amalgamate clay soil with nano-silica and polypropylene fiber. In addition, to grasp the microstructural modifications resulting from the integration of Nano-SiO₂ and PPF. Alongside polypropylene fiber, four separate formulations of nano-silica at diverse percentages—1%, 3%, 5%, and 7%—are applied in differing amounts, such as 0.1%, 0.4%, 0.7%, 1%, and 1.3%.

Tebogo Pilgrene Mashifana et al (2018) To assess the feasibility of stabilizing extensively abundant expansive soil, a larger volume of phosphogypsum waste was employed as a potential additive, leading to the

formulation of composites that included lime, fly ash, phosphogypsum, and basic oxygen furnace slag. The presence of radionuclides necessitated the treatment of phosphogypsum waste using mild citric acid. The influence of acid treatment on the geotechnical attributes and microstructure of expansive soil stabilized by phosphogypsum-lime-fly ash-basic oxygen furnace slag (PG-LFA-BOF) paste was analyzed, in contrast to untreated phosphogypsum. Stabilizing expansive soil with acid-treated PG-LFA-BOF paste resulted in enhanced geotechnical attributes; specifically, the considerable strength realized was chiefly linked to the synthesis of multiple calcium magnesium silicide and the encasement of calcium silicate hydrate and calcium aluminate hydrate. The progression of hydration products facilitated an augmentation of the soil microstructure. The expansive soil, once stabilized, satisfied the criteria for road subgrades and subbase.

Suresh et al. (2018) this review article examines the characteristics of clayey soil enhanced with different proportions (0.5-10%) of coir fiber and Nano silica, through the assessment of the index and engineering features of the soils. Coir is a naturally occurring biodegradable substance that is plentiful in certain areas of southern and coastal India. Nano silica, as diminutive filler materials, enhances ductility without compromising strength. The nano silica's induction functioned as a hydraulic binder with reduced swelling capacity. The amalgamation of coir fiber and Nano silica is employed in expansive soils for the goal of sustainable development.

OBJECTIVES OF THE STUDY

The aims of the research endeavor are:

1. To ascertain the fundamental characteristics and Atterberg limits of the unprocessed clay soil.
2. To investigate the effect of phosphogypsum (15%, 20%, and 25%) and nano-silica (1.0%, 1.5%, and 2.0%) on the compaction characteristics of clay soil.
3. To evaluate the influence of different combinations of phosphogypsum and nano-silica on the Unconfined Compressive Strength (UCS) and California Bearing Ratio (CBR) of modified clay soil.
4. To determine the optimal combination of phosphogypsum and nano-silica based on improvements in compaction, UCS, and CBR characteristics.

5. To examine the efficacy and sustainability of phosphogypsum and nano-silica as stabilizers for improving the engineering characteristics of clay soil.

3. Materials

3.1 soil The excavated soil from the area was crushed into chunks using a wooden hammer and subsequently left to dry outdoors under protection. It was meticulously combined and then subjected to a 2.35 mm IS sieve. The requisite volume of dirt for every test was taken from polythene bags and subjected to drying at 105°C/5°C for a whole day. The ground was permitted to cool to a temperature consistent with the surroundings. The distinct attributes of untainted soil that are applied encompass:

Table no. 1 Properties of soil used in the study

S No.	Properties	Results
1	Specific gravity	2.70
3	Liquid Limit (%)	51.91 %
4	Plastic Limit (%)	26.76 %
5	Plasticity index (%)	25.15 %
6	Classification of soil	CH
7	Maximum Dry Density (kN/m ³)	15.10 kN/m ³
8	Optimum Moisture Content (%)	16.01 %
9.	U.C.S (7 Days)	96 kN/m ²
10.	U.C.S (7 Days)	130 kN/m ²
11.	CBR (%)	1.7 (Soaked)
		2.5 (unsoaked)

3.2 PHOSPHOGYPSUM

An industrial byproduct produced when phosphoric acid is made from phosphate rock is phosphogypsum (PG). It is manufactured in extensive amounts and is chiefly made up of calcium sulfate dihydrate (CaSO₄•2H₂O), containing small traces of organic material, silica, fluorides, residual phosphates, and other mineral impurities. Phosphogypsum has garnered a lot of interest for use in soil stabilization and civil engineering because of its calcium and sulfate concentration.

Table 2: Chemical Properties of Phosphogypsum

S. No	Name of constituent	Percentage
1	SiO ₂	43.6
2	Al ₂ O ₃ + Fe ₂ O ₃	1.82
3	Calcium Oxide (CaO)	32.0
4	Magnesium oxide (MgO)	0.40
5	SiO ₂ ins. In HCl	1.64
6	Na ₂ O	0.36
7	P ₂ O ₅	1.03
8	Organic matter	0.26

3.3 NANO SILICA

The addition of nano-silica to soil can optimize its features, lower hydraulic conductivity, and elevate its strength. It may elevate the unconfined compressive and shear strengths of clay soils and bolster soils that have been treatment with fiber, cement, and lime. Tables 3 and 4 delineate the features of Nano Silica.

Table 3 Physical properties of Nano-silica

Physical properties	Value
Diameter (nm)	20 – 30
Surface volume ratio (m ² /g)	193
Density (g/cm ³)	1.7
Purity (%)	>99

Table 4 Chemical properties of Nano-silica

Sr. No.	Compound	Value (%)
1	Silicon	99.88

	Oxide(SiO ₂)	
2	Al ₂ O ₃	0.05
3	Iron Oxide (Fe ₂ O ₃)	0.01
4	Carbon content	0.06
5	Chloride content	0.09

4. EXPERIMENTAL RESULTS

For experimental study different nomenclatures have been prepared with different proportions of ingredients, which have been shown below:

4.1 Mix Proportion Used

Table no. 4.0: Various Mix proportions of Soil, Phosphogypsum and Nano-silica

S.N.	Nomenclature	Description of the additives added with the soil		
		Soil (%)	Phosphogypsum by (%) of weight of soil	Nano-silica by (%) of weight of soil
1.	S	100	0	0
2.	S1	85	15	0
3.	S2	80	20	0
4.	S3	75	25	0
5.	S4	99.0	0	1.0
6.	S5	98.5	0	1.5
7.	S6	98.0	0	2.0
8.	S7	79.5	20	0.5
9.	S8	79.0	20	1.0
10.	S9	78.5	20	1.5

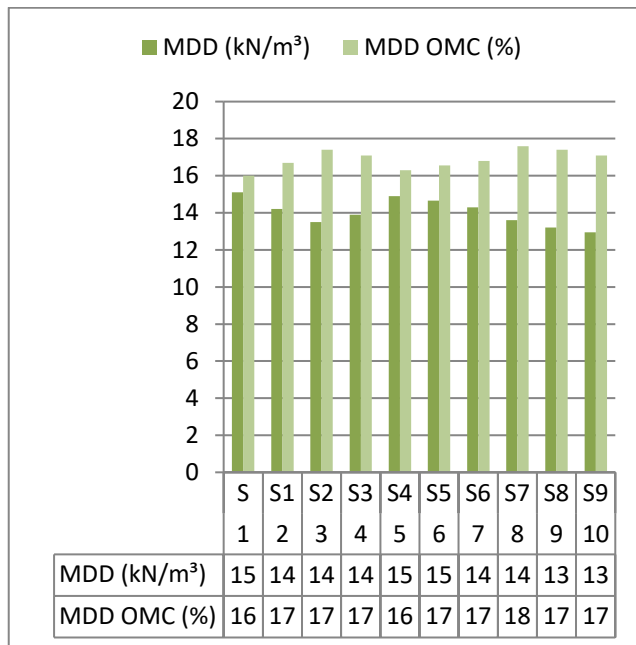
4.1 STANDARD PROCTOR TEST

The laboratory evaluation comprises various levels of 0.5%, 1.0%, and 1.5% Nano-Silica, with 20% Phosphogypsum designated as an invariant variable. The following figures indicate the effect of varying percentages of Phosphogypsum and Nano-Silica on the desired moisture content and dry density. The essential parameters that markedly influence the integrity and endurance of pavements laid on subgrades are the compaction qualities of the soil. Subgrade soil developed at the optimal moisture content (OMC) can ensure and maintain adequate stability under various load types during the critical timeframe. The compaction guidelines are crucial for securing the desired sustainability of the pavement, as represented in figure 1 and recorded in table 4.1.

Table 4.1: Results of OMC and MDD for mix proportions of Soil, Phosphogypsum and Nano Silica

S No.	Soil Sample	MDD (kN/m ³)	OMC (%)
1.	S	15.10	16.01
2.	S1	14.20	16.70
3.	S2	13.50	17.40
4.	S3	13.90	17.10
5.	S4	14.90	16.30
6.	S5	14.65	16.55
7.	S6	14.30	16.80
8.	S7	13.60	17.60
9.	S8	13.20	17.40
10.	S9	12.95	17.10

Fig: 1 Variations b/w MDD and OMC of Phosphogypsum, Nano-Silica & soil with different Ratios



- When the percentages of phosphogypsum are adjusted to 15, 20, and 25%, the OMC increases from 16.01 to 17.10% and the MDD decreases from 15.10 to 13.90%.
- The OMC rises from 16.01% to 16.80%, while the MDD declines from 15.10% to 14.30% when the proportions of Nano-Silica fluctuate between 1.0%, 1.5%, and 2.0%.
- When the proportions of Nano-Silica are modified to 0.5, 1.0, and 1.5%, while phosphogypsum remains at 20%, the Maximum Dry Density (MDD) diminishes from 15.10 to 12.95%, while the Optimum Moisture Content (OMC) rises from 16.01 to 17.10%.

4.2 CALIFORNIA BEARING RATIO TEST

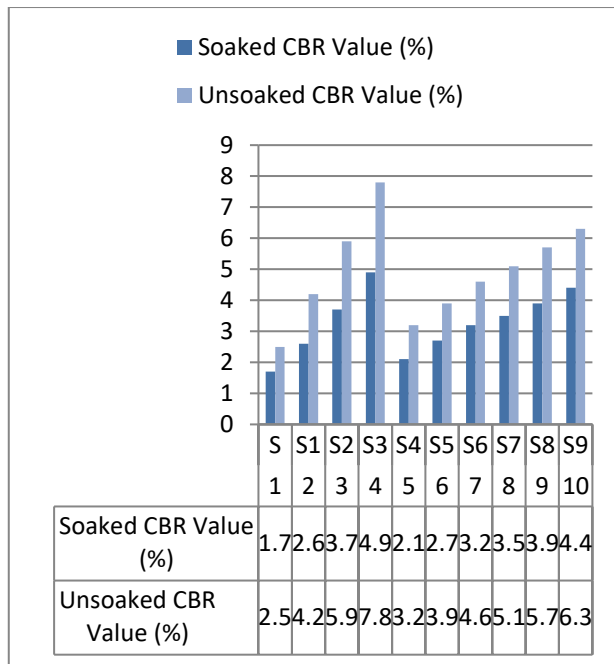
The assessment of laboratory tests utilizes various combinations of 0.5%, 1.0%, and 1.5% Nano-Silica, while keeping 20% Phosphogypsum constant. The California bearing ratio (CBR) of the subgrade functions as a crucial strength metric for assessing the thickness of the pavement's subgrade. IS: 2720 (Part 16) - 1987 indicates that clay subgrades exhibit low California Bearing Ratio values. The California Bearing Ratio of the clay subgrade needs enhancement with the application of several

admixtures. The California bearing ratio test was employed for conventional compaction outcomes in both drenched and unsoaked conditions. The proportions of a constant 20% Phosphogypsum mixed with 0.5%, 1.0%, and 1.5% Nano-Silica are depicted in figure 2 and recorded in table 4.2.

Table 4.2: Results of CBR Values for mix proportions of Soil, Phosphogypsum and Nano-Silica

S No.	Soil ample	Soaked CBR Value (%)	Unsoaked CBR Value (%)
1.	S	1.7	2.5
2.	S1	2.6	4.2
3.	S2	3.7	5.9
4.	S3	4.9	7.8
5.	S4	2.1	3.2
6.	S5	2.7	3.9
7.	S6	3.2	4.6
8.	S7	3.5	5.1
9.	S8	3.9	5.7
10.	S9	4.4	6.3

Fig: 2 Variations CBR values of Phosphogypsum, Nano-Silica & soil with different Ratios



- The CBR value increases from 1.7 to 4.9 when phosphogypsum is added at varying ratios, such as 15%, 20%, and 25%, in soaked conditions.
- The CBR value rises from 3.5 to 4.4 when 20% Phosphogypsum is incorporated and Nano Silica is introduced in varied proportions of 0.5%, 1.0%, and 1.5%.
- The CBR value of the soil is 1.7, which escalates to 2.58 times with the incorporation of 20% phosphogypsum and 1.5% nanosilica under saturated circumstances.

Table 4.3: Results of UCS Values for mix proportions of Soil, Phosphogypsum and Nano-Silica

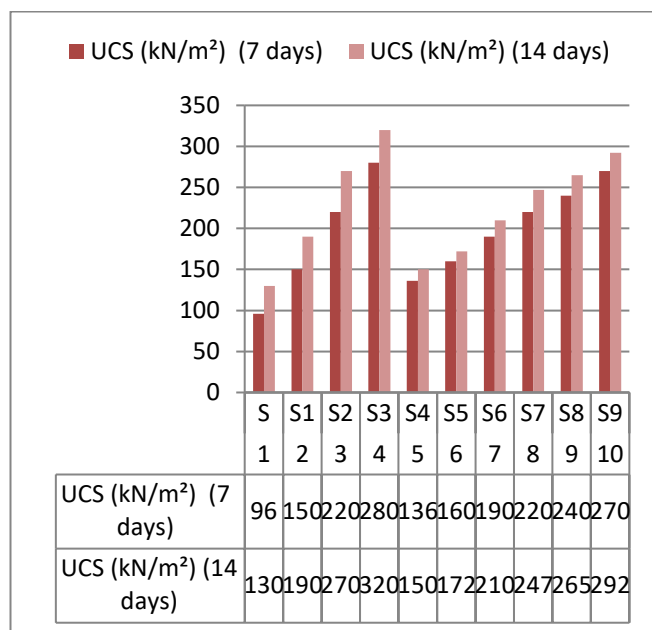
S No.	Soil Sample	UCS (kN/m ²) (7 days)	UCS (kN/m ²) (14 days)
1.	S	96	130
2.	S1	150	190
3.	S2	220	270
4.	S3	280	320
5.	S4	136	150
6.	S5	160	172
7.	S6	190	210
8.	S7	220	247
9.	S8	240	265
10.	S9	270	292

4.3 UNCONFINED COMPRESSION STRENGTH TEST

The laboratory examination incorporates varied ratios of 0.5%, 1.0%, and 1.5% Nano-Silica and constant 20% Phosphogypsum.

The UCS test was conducted at a steady strain rate of 0.125 mm/minute on both reinforced and unreinforced soil specimens according to IS: 2720 (part-10). The unconfined compressive strength characteristics of different combinations are examined under compressive stress, and the final results are cataloged in table 4.3 and shown in Figure 3.

Fig: 3 Variations UCS values of Phosphogypsum, Nano-Silica & soil with different Ratios



- The UCS value of soil significantly enhances with the incorporation of Phosphogypsum at 15%, 20%, and 25% throughout a curing duration of 7 days.
- The UCS value of soil significantly enhances with the incorporation of 20% Phosphogypsum and 1.5% Nano Silica after a curing duration of 7 days. The value escalates from 96kN/m² to 260kN/m² with the incorporation of Phosphogypsum and Nano Silica.
- The UCS value of soil significantly enhances with the incorporation of 20% Phosphogypsum and 1.5% Nano Silica after a curing duration of 14 days. The value escalates from 130kN/m² to 292kN/m² with the incorporation of Phosphogypsum and Nano Silica.

5. DISCUSSIONS

STANDARD PROCTOR TEST:

- The OMC rises from 16.01% to 17.10%, whereas the MDD declines from 15.10% to 13.90% as the proportions of Phosphogypsum fluctuate between 15%, 20%, and 25%. The decrease in MDD with higher phosphogypsum levels may be ascribed to alterations in soil particle configuration and the development of a comparatively more permeable framework. Consequently, the synergistic influence of modified particle arrangement and heightened moisture requirements results in a reduction of MDD and an elevation of OMC.

- The MDD decreases from 15.10% to 12.95%, and the OMC increases from 16.01% to 17.10% as the concentrations of Nano-Silica vary between 0.5, 1.0, and 1.5%, with Phosphogypsum held constant at 20%. The incorporation of nano-silica into clayey soil with 20% phosphogypsum led to a gradual decline in MDD and a rise in OMC as the nano-silica concentration increased from 0.5% to 1.5%.
- The diminishment of MDD can be ascribed to the exceedingly fine characteristics of Nano-silica and its propensity to create agglomerates, which may disrupt the effective arrangement of soil and phosphogypsum particles, leading to a comparatively more porous compacted configuration. Additionally, the reduction in dried density may be attributed to the alteration of the soil fabric as a result of interactions between nano-silica, clay particles, and phosphogypsum.
- The increase in OMC can primarily be attributed to the remarkably high specific surface area of nano-silica, which enhances the volume of water required for particle wetting, lubrication, and effective reorganization during compaction. Consequently, augmenting the nano-silica concentration elevates the water need while diminishing the attainable dry density given the exerted compactive effort.

CBR TEST:

- The addition of nano-silica (0.5–1.5%) to clayey soil stabilized with 20% phosphogypsum resulted in an enhanced CBR value. This progress can be attributed to the micro-filling properties of nano-silica, increased interaction among soil particles, and improved cohesiveness in the soil structure. The ultrafine nano-silica particles mitigate weak regions and foster a more compact and stable particle network, thereby enhancing the soil's resistance to penetration and improving its load-bearing ability.
- The enhancement of CBR linked with increasing levels of nano-silica illustrates the successful application of 20% phosphogypsum mixed with nano-silica in advancing the engineering properties of clay soil.

UCS TEST:

- The addition of 20% phosphogypsum (PG) combined with 0.5%, 1.0%, and 1.5% nano-silica (NS) can significantly improve the unconfined compressive strength of clay soil. Phosphogypsum alters the configuration of clay particles and introduces calcium and sulfate-rich elements to the stabilized composition. The integration of ultrafine nano-silica facilitates a micro-filling effect, enhancing the interaction among soil particles and diminishing weak areas within the soil matrix.
- An elevation in nano-silica levels contributes to a larger specific surface area, which facilitates superior interactions with soil particles and bolsters the cohesiveness of the soil matrix. In the presence of appropriate reactive components, nano-silica can engage in secondary cementitious processes, aiding in the generation of supplementary binding products.
- As a result, the amended soil exhibits a more robust and stable internal composition, leading to an enhancement in UCS relative to untreated clay soil. The enhancement in UCS illustrates the capability of the 20% PG + 0.5–1.5% NS mixture for the sustainable stabilization of clayey soil.

6. CONCLUSIONS

Based on experimental findings, the subsequent conclusions have been reached:

1. Essential Attributes and Atterberg Limits:

The essential characteristics and Atterberg limits of the raw clayey soil were identified to set a reference point for measuring stabilization efficiency. These initial traits formed a framework for analyzing the modifications in the soil's consistency and engineering performance post-treatment with phosphogypsum and nano-silica.

2. Compaction Properties:

The introduction of phosphogypsum and nano-silica influenced the compaction properties of the clayey soil. The maximum dry density (MDD) was 12.95 kN/m^3 in the specified blend of 20% phosphogypsum and 1.5% nano-silica, while the optimum moisture content (OMC) was recorded at 17.10%. The increase in OMC and the reduction in MDD are the result of the high specific

surface area of nano-silica, more void spaces, and modifications in particle organization. This results in a greater need for hydration during compaction.

3. CBR Effectiveness:

The modified soil revealed superior resistance to penetration, with a soaked CBR of 4.4% and an unsoaked CBR of 6.3% for the 20% phosphogypsum and 1.5% nano-silica blend. The advancement may be attributed to the micro-filling properties of nano-silica, augmented particle interactions, and superior bonding within the stabilized soil composition. The increased unsoaked CBR relative to the soaked CBR also signifies the impact of water saturation on the bearing strength of the treated soil.

4. UCS Effectiveness:

The resilience of the stabilized soil improved as the curing period extended. The UCS for a mixture containing 20% phosphogypsum and 1.5% nano-silica was measured at 270 kN/m^2 after 7 days of curing, increasing to 292 kN/m^2 after 14 days. This progress denotes the evolution of enhanced interparticle adhesion through curing and could be related to continuous physicochemical interactions within the stabilized soil composition. The escalation from 270 to 292 kN/m^2 denotes an advancement of about 8.1% in the strength measured after 7 days.

5. Overall Suitability and Optimum Combination:

The analysis of engineering parameters revealed that the blend of 20% phosphogypsum and 1.5% nano-silica showed favorable stabilization results, featuring a maximum dry density of 12.95 kN/m^3 , optimum moisture content of 17.10%, soaked CBR of 4.4%, unsoaked CBR of 6.3%, 7-day UCS of 270 kN/m^2 , and 14-day UCS of 292 kN/m^2 . The outcomes reveal the promise of phosphogypsum and nano-silica as potent stabilizers for augmenting the strength and load-bearing capacity of clayey soils, simultaneously fostering the productive use of an industrial by-product.

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