Lecture Notes in Civil Engineering

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Anand J. Puppala ·
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Benny Mathews Abraham ·
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Geotechnics: Learning, Evaluation, Analysis and Practice (GEOLEAP)

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Preface

The Indian Geotechnical Society, Kochi (IGS-Kochi) Chapter, in association with Cochin University of Science and Technology (CUSAT), India, organized the Indian Geotechnical Conference (IGC-2022) at Kochi during 15–17 December 2022. The main theme of the conference was "**GEOLEAP—GEO**TECHNICS: **L**EARNING, **E**VALUATION, **A**NALYSIS AND **P**RACTICE".

The sub-theme of the conference includes:

1. Behaviour of Soils and Soil–Structure Interaction
2. Soil Stabilization, Ground Improvement and Land Reclamation
3. Shallow and Deep Foundations
4. Geotechnical, Geological and Geophysical Investigation
5. Rock Engineering, Tunnelling and Underground Structures
6. Slope Stability, Landslides and Liquefaction
7. Earth Retaining Structures and Deep Excavations
8. Geosynthetics Engineering
9. Geo-Environmental Engineering, Sustainable Geotechnics and Landfill Design
10. Geohydrology, Dam and Embankment Engineering
11. Earthquake Geotechnical Engineering
12. Transportation Geotechnics
13. Forensic Geotechnical Engineering and Retrofitting of Geotechnical Structures
14. Offshore Geotechnics, Marine Geology and Subsea Site Investigation
15. Computational, Analytical and Numerical Modelling
16. Reliability in Geotechnical Engineering.

The proceedings of this conference consist of selected papers presented at the conference, organized into five volumes. The keynote and theme lectures presented during IGC-2022 are being published as a special issue of the *Indian Geotechnical Journal*.

We sincerely thank all the authors who have contributed their papers to the conference proceedings. We also thank all the theme editors and reviewers who have been instrumental in giving their valuable inputs for improving the quality of the final papers. Finally, we thank the Springer team for their support and full cooperation for publishing these five volumes of IGC-2022 proceedings.

Kochi, India

Dr. Babu T. Jose
Chairman IGC-2022

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About the Editors

Dr. Babu T. Jose completed his B.Tech. from NIT Warangal in 1967 with Nehru Memorial Gold Medal, M.Tech. from IIT Madras in 1972 and Ph.D. from Cochin University of Science and Technology in 1990. He was a lecturer in NIT, Calicut, for 13 years (1967–1980). Currently, he is an emeritus professor at Cochin University of Science and Technology since 2004. Dr. Jose has commendable experience in research. He has published more than 200 research papers, and on the consultancy front, he has successfully completed more than 500 projects. On the administrative side, he was a principal at the School of Engineering, Cochin University, during 1980–1995 and a director of two engineering colleges from 1985 to 2004. Dr. Babu T. Jose is the founder chairman of IGS, Kochi Chapter. He was the chairman of the organizing committee of IGC in 2011 and the chief editor of its proceedings.

Dr. Dipak Kumar Sahoo has been a full-time faculty member since 2001, and currently a professor since 2009, in the School of Engineering, Cochin University of Science and Technology, Kochi. Prior to academics, he was working in the Fertilizers and Chemicals Travancore Limited, a Central Public Sector Company, in India for more than ten years as a consulting engineer to many public and private sector companies for setting up their green-field petrochemical complexes in different parts of India. He received his B.Sc. Engineering (Civil) from CET Bhubaneswar in 1987, M.Tech. in Construction Engineering and Management from Cochin University of Science and Technology in 1998, Ph.D. in Structural Engineering from the Indian Institute of Technology Roorkee in 2009 and LL.B. from the Cochin University of Science and Technology in 2015.

Dr. Anand J. Puppala currently serves as A. P. Wiley and Florence Chair of Zachry Civil and Environmental Engineering at Texas A&M University and has been an Associate Director of Center for Infrastructure Renewal (CIR) since 2019. Dr. Puppala was the chair of Soil Mechanics section (AFS00) of the Transportation Research Board (TRB). He also chaired American Society of Civil Engineers (ASCE)'s Geotechnical Institute's (GI) "Engineering Geology and Site Characterization" committee and TRB committee on "Soil and Rock Instrumentation."

Dr. Puppala is the current chair of ISSMGE's Technical Committee 307 on Sustainability in Geotechnical Engineering. He has given several keynotes and invited talks worldwide, including a prestigious ASCE GI Peck talk at 2020 GeoCongress Meeting held in Minneapolis, Minnesota.

Dr. C. N. V. Satyanarayana Reddy is a professor of Civil Engineering at College of Engineering, Andhra University, Visakhapatnam, and has 29 years of teaching, research, and consultancy experience. His expertise and research interests are in the areas of reinforced soils, ground improvement, landfills, soil retention in excavations, deep foundations, and forensic geotechnical engineering. He obtained B.Tech. (Civil Engineering) degree securing first rank from Nagarjuna University, M.Tech. (Geotechnical Engineering) degree from IIT Madras, M.E. (Structures) from Andhra University, and Ph.D. from NIT Warangal. He has guided 9 Ph.D. scholars and 105 M.Tech. Dissertations so far. He has more than 110 publications in various national and international journals and seminar and conference proceedings. He served as a director of Andhra University Development Centre during the period 2013–2017.

Dr. Benny Mathews Abraham graduated from Regional Engineering College Calicut in 1982. He completed his M.Tech. from IIT Madras in 1984 and Ph.D. from Cochin University in the year 1994. He joined Cochin University as a lecturer in 1985 and became a professor in the year 2001. He was the head of Division of Civil Engineering, CUSAT, for 13 years and was the dean of Faculty of Architecture, CUSAT for three years. He was the chairman of Board of Studies and Academic Council at CUSAT. He retired from Cochin University service in May 2020, and currently, he is the professor and head of the department at Albertian Institute of Science and Technology, Kalamassery. He has more than 80 publications out of which 25 are in peer-reviewed international journals. He won the IGS best research paper awards in 1989, 1991, and 2016.

Mr. Ravikiran Vaidya, Principal Engineer of Geodynamics, has been instrumental in popularizing the concept of Deep Foundation Testing in India. He has created a deep foundation testing industry and today Geo Dynamics is India's premier testing company in this field. Jointly with Dr. Jaykumar Shukla, he has also indigenized and successfully demonstrated bi-directional load testing even for large-capacity monopiles which is yet another milestone for the country. Thermal integrity profiling and instrumentation have been his other contributions. He has worked on almost all the prestigious projects in the country and in more than 20 countries worldwide. He has written more than 21 technical papers in conferences and journals. He was the co-editor of the Indian Geotechnical Conference, Vizag, in 2020. He has guided several master's theses, and his work has been used by students in their Ph.D. thesis.

Soil Stabilization, Ground Improvement and Land Reclamation

Geotechnical Benign Characterization of Nano-amended CLS Stabilized Soil

Harshit Harsh, Arif Ali Baig Moghal, and Romana Mariyam Rasheed

1 Introduction

A rapid increase in infrastructural development had driven engineers to suitably modify the properties of undesirable in-situ soils using chemical additives such as lime and cement [1–3]. Though the use of such chemical additives has significantly improved the properties of soils, they have also substantially contributed to the increase in carbon footprint emissions released during their production and service life. Therefore, a gradual transition from carbon-based additives to sustainable materials is witnessed in soil stabilization and remediation [4]. The emergence of nanotechnology in science and technology has significantly helped in achieving this transition [5, 6]. Nanotechnology has been applied across many fields such as medicine, engineering, environment, communication, and heavy industry. These materials have significantly enhanced the engineering properties of materials in civil engineering and construction by reducing the energy consumption of structures, environmental impact, and cost associated with structures [7–11].

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The current study investigates the effect of nano-Fe_2O_3 in the enhancement of compaction characteristics, and compressive strength. The use of calcium lignosulfonate (CLS) as an initiator along with nano-Fe_2O_3 has also been explored. Nano-Fe_2O_3 and CLS have been used in various proportions (0.1–0.3% and 1–3%, respectively) to stabilize the soil. The changes in the microstructure of the soil samples have also been determined for the various nanosoil mixes.

2 Materials and Methods

2.1 *Soil and Nano-Fe_2O_3 Properties*

Soil investigated and evaluated in the current study was stockpiled from a site in Batpalli cheruvu, located in the Telangana State of India. The soil was treated with nano-Fe_2O_3 in the presence of CLS to determine the improvement in the strength of the soil. The nano-Fe_2O_3 was procured from AD-Nano Tech Research Lab in Karnataka along with a characteristics report and contains about 99% iron oxide. Whereas, CLS was procured from Venki Chem, Mumbai, India. Other elements such as chromium, phosphorous, sodium, manganese, sulfur, and calcium, constituted 1% of the powder. The characteristics of nano-Fe_2O_3 used for the study are discussed in Table 1.

Wet sieve analysis was carried out in accordance with IS:2720 Part 4-1985 [12], wherein the coarser fraction was observed to be 40.7%, and the finer fraction passing 75 μm was 59.3%. Hence, the soil was termed fine-grained soil. For further classification of soil, other basic tests were conducted. Atterberg limit test was done in accordance with IS:2720 Part 5-1985 [13], and subsequently, Liquid Limit (LL), Plastic Limit (PL), and Shrinkage Limit (SL) of soil were found to be 55.8, 20.1, and 12.7%. The plasticity index (PI) of soil tested was 35.6%, and PI, corresponding to A-Line, was 26.1%. Based on Atterberg limits, gradation characteristics, and Unified Soil Classification System, the soil was classified as fat clay (CH) [14]. The particle size gradation curve is depicted in Fig. 1.

Table 1 Physical properties of nano-Fe_2O_3

S. No.	Properties	Value
1	Average particle size (APS)	40 nm
2	Specific surface area (SSA)	90 m^2/g
3	Molecular weight	159.69 g/mol
4	Melting point	1565 °C
5	pH	5–7
6	Bulk density	0.69 g/cc
7	Morphology	Spherical
8	Colour	Red

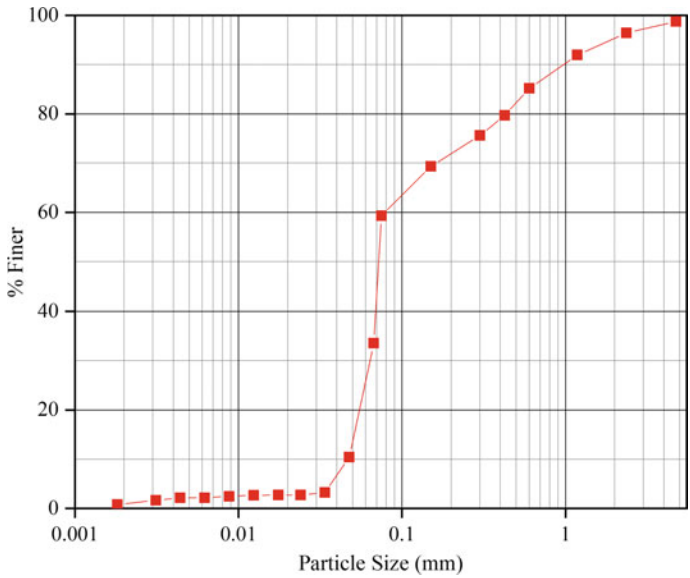

Fig. 1 Particle size distribution curve of the soil used in the study

The samples were prepared at OMC and MDD for various tests. The compaction test was carried out in accordance with IS:2720 Part 7-1980 [15]. After completing the standard proctor test on 16 uncured samples with different proportions of nano-Fe_2O_3 and CLS, OMC, and MDD were obtained as 16.5% and 1.835 g/cc, respectively, for a combination of 0.2% nano-Fe_2O_3 and 2% CLS. The other basic properties were also determined in accordance with IS codes. The Free Swell Index (FSI) of the soil [16] was 85.7%, and specific gravity [17] was 2.685. Table 2 presents the geotechnical properties of the soil.

The unconfined compression strength test in saturated clay was determined in accordance with IS:2720 Part 10-1991 [18]. In the current study, samples (76 mm

Table 2 Geotechnical properties of soil

S. No.	Properties	Value
1	Liquid limit	55.7%
2	Plastic limit	20.1%
3	Plasticity index	35.6%
4	Shrinkage limit	12.66%
5	Specific gravity	2.685
6	Free swell index	85.7%
7	Optimum moisture content	18%
8	Maximum dry density	1.7 g/cc
9	Soil classification (USCS)	CH

in length and 38 mm in diameter) prepared at optimum conditions and treated with NMs and CLS were tested after a curing period of 7, 14, and 28 days at a loading rate of 1 mm/min. The soil fabric for untreated samples and samples treated with different proportions of nano-Fe_2O_3 and CLS was studied using scanning electron microscopy (SEM).

2.2 Sample Preparation

As suggested by Pakbaz and Farzi [19], a dry mixing procedure was adopted for sample preparation. The nano-Fe_2O_3 powder was sprayed over the oven-dried soil to prepare the nanosoil mixture. According to this method, 0.1, 0.2, and 0.3% of nano-Fe_2O_3 were taken by dry weight of soil and blended along with 1–3% of CLS. A homogenous mix was obtained by thoroughly mixing the soil at OMC utilizing a spatula for about 5–10 min before placing the soil sample in the mold.

3 Results and Discussions

3.1 Effect of Nano-Fe_2O_3 on Atterberg Limit

As the proportion of nano-Fe_2O_3 is increased, stabilized soil shows a gain in plastic Limit (PL) and a drop in Liquid Limit (LL), and hence Plasticity Index (PI) of the soil is reduced, as depicted in Fig. 2. The LL and PI of stabilized soil reduced with an increase in nanomaterial concentration, owing to the water adsorbing capacity and non-plastic nature of nano-Fe_2O_3.

3.2 Effect of Nano-Fe_2O_3 and CLS on Compaction Characteristics

With the addition of nano-Fe_2O_3, a gain in MDD was visible up to 0.3%, and up to 2% of CLS when they were added independently. When the stabilizers were added together, the optimum combination was observed at 0.2% nano-Fe_2O_3 and 2% CLS, where the least OMC and highest MDD were obtained. The increase in dry density can be attributed to the filling of the voids by nanoparticles, and ultimately increasing the unit mass of soil. The decrease in MDD beyond the optimum content is due to flocculation and agglomeration of nanoparticles as a result of cation exchange capacity and low specific gravity of nanoparticles which is generally less than soil [20–22], whereas Optimum Moisture Content (OMC) decreased due to the ion exchange mechanism during the chemical reaction. In a few cases, there was an

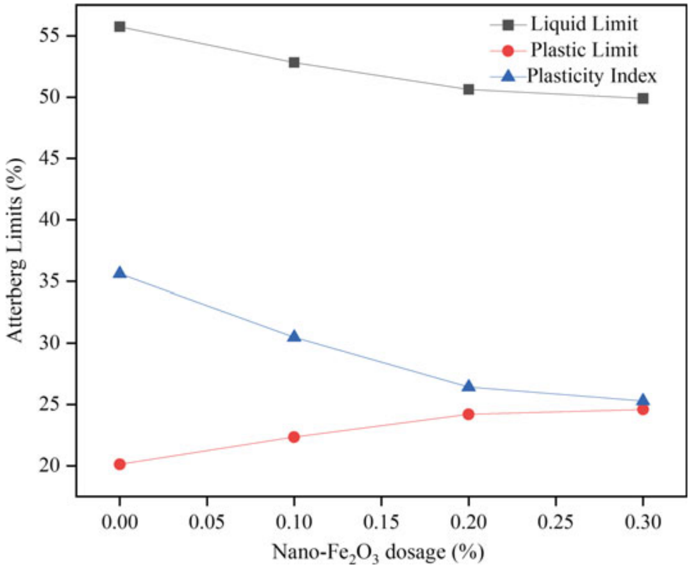

Fig. 2 Change in Atterberg limits with the variation of nano-Fe_2O_3

increase in OMC suggesting the occurrence of pozzolanic reaction [23]. Variation in OMC and MDD is depicted in Figs. 3, 4, and 5. The mix notations for various combinations of nano-Fe_2O_3 and CLS are presented in Table 3.

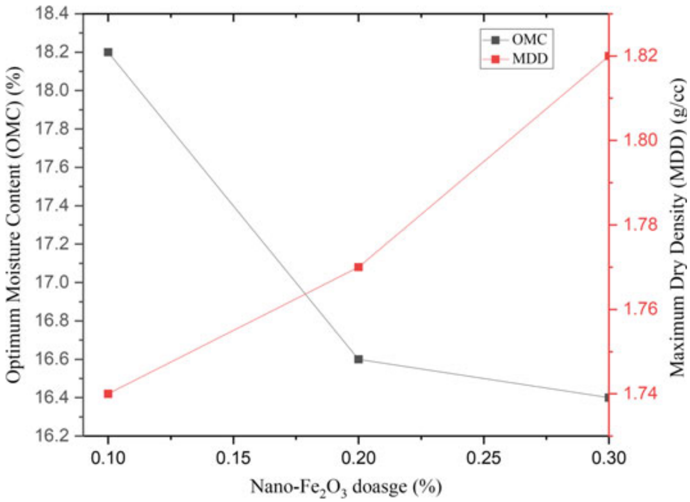

Fig. 3 Variation in OMC and MDD with nano-Fe_2O_3

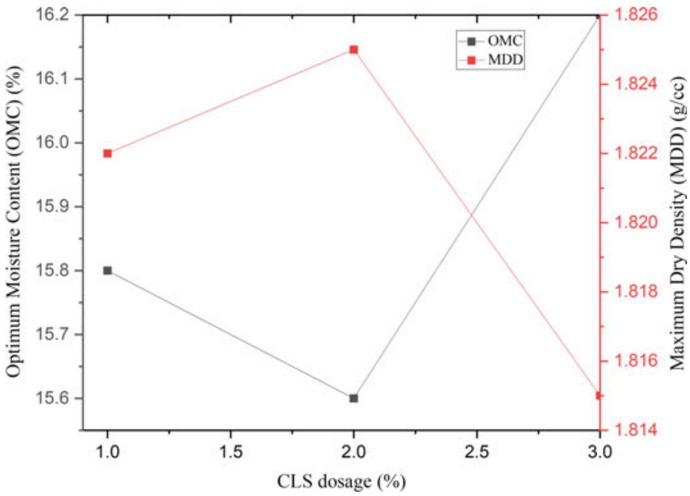

Fig. 4 Variation in OMC and MDD for CLS mixes

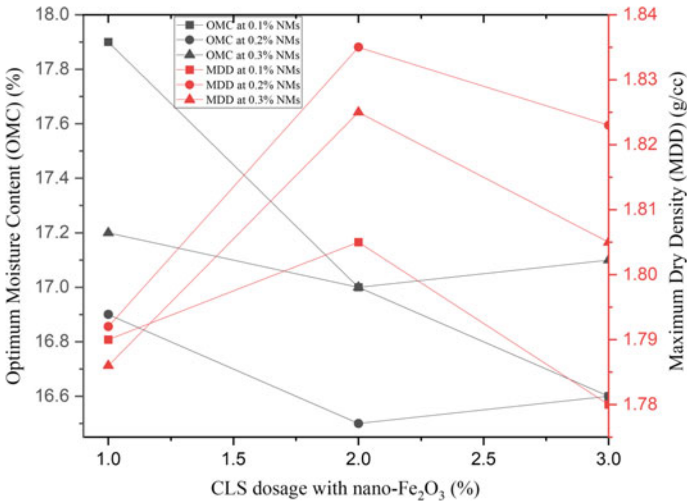

Fig. 5 Variation in OMC and MDD when nano-Fe_2O_3 is blended with CLS

3.3 Effect of Nano-Fe_2O_3 on Strength Characteristics

Figure 6 depicts the variation in UCS upon treatment with nano-Fe_2O_3 and CLS. When nano-Fe_2O_3 and CLS were added independently, the UCS value increased up to 0.2% and 2% respectively, beyond which the compressive strength reduced. For the varying concentrations taken for nano-Fe_2O_3 and CLS, the UCS value increased with an increase in the curing period. Nanoparticles, which are very small in size,

Table 3 Mix notations adopted in the study

D	U	0.1% NM	0.2% NM	0.3% NM	1% CLS	2% CLS	3% CLS	0.1%NM + 1% CLS	0.1%NM + 2% CLS	0.1% NM + 3% CLS	0.2%NM + 1%CLS	0.2%NM + 2%CLS	0.2%NM + 3% CLS	0.3%NM + 1%CLS	0.3%NM + 2%CLS	0.3%NM + 3% CLS
M	M0	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15

* *D* dosage, *M* mix notation, *U* untreated soil, *NM* nano-Fe_2O_3 and *CLS* calcium lignosulfonate

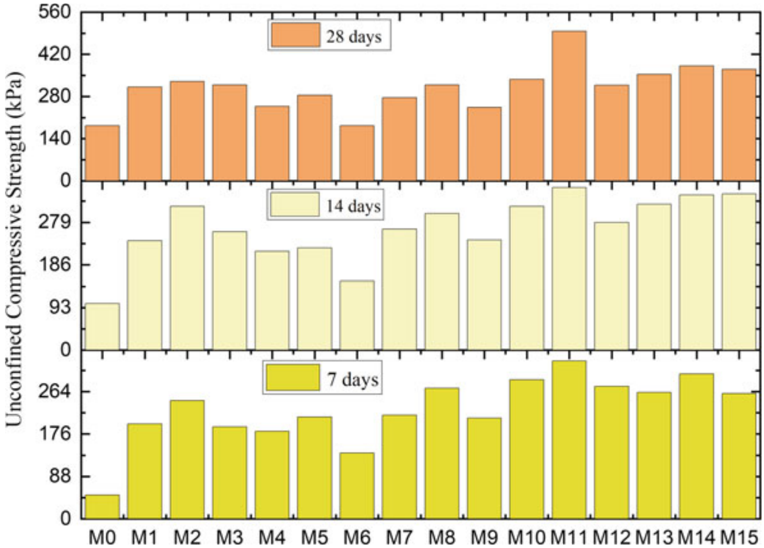

Fig. 6 Variation in unconfined compressive strength upon treatment at 7, 14, and 28 days

have a vast surface area and hence will exhibit high chemical reactivity [24]. When nanomaterial comes in contact with lime, cement, or calcareous compounds, it leads to the genesis of C–S–H gel due to the pozzolanic reaction.

The porosity of soil is reduced as nanomaterial is absorbed onto C–S–H gel, hence aiding in improving the compressive strength [25]. Generally, the compressive strength of montmorillonite soil is constituted by viscous diffused double layer water to the shear formation [26]. As the soil used for the test has low fine contents, it will require a lower polymer chain to bind clay particles; and any additional polymer chain creates reciprocal repulsive force among the charged parts [27], leading to a reduction in UCS.

3.4 Microstructural Analysis

The SEM analysis was conducted on untreated soil, and soils blended with 0.2% NM, 0.2% NM + 2% CLS, and 0.2% NM + 3% CLS to observe the soil fabric. Soil combined with 0.2% nano-Fe_2O_3 contributed to the maximum improvement when blended individually. Similarly, when nano-Fe_2O_3 and CLS were used together in soil, the maximum improvement in soil was observed at 0.2% nano-Fe_2O_3 and 2% CLS. These values were then considered as optimum content. Further addition of CLS beyond 2% led to a negative improvement in strength.

Figure 7a depicts the SEM image of untreated soil, in which the pores and voids can be clearly observed. The cavities present in the soil are the main reason for

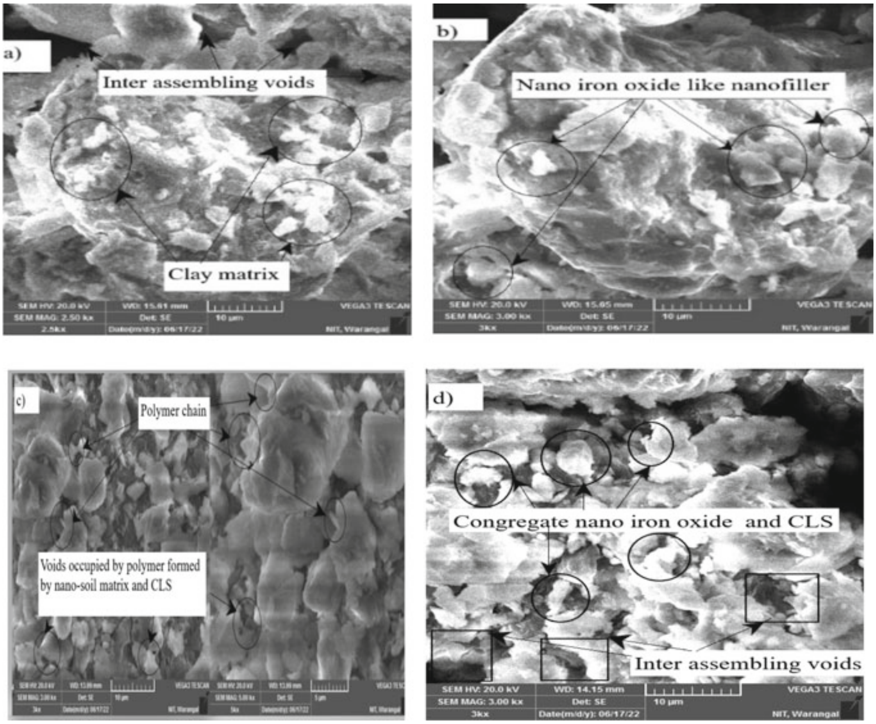

Fig. 7 SEM images of treated and untreated soil. **a** M0, **b** M2, **c** M11, **d** M12

the lower strength of the soil. Figure 7b demonstrates the soil blended with 0.2% nano-Fe_2O_3. As the size of nano-Fe_2O_3 is much less than voids of the soil particles, increasing the nanoparticles up to a certain fraction increases the soil strength as it occupies the cavities present in the soil matrix, developing the continuity among particles and acts as filler material.

Figure 7c depicts an SEM image when 0.2% nano-Fe_2O_3 is blended with 2% CLS. Here CLS addition leads to the formation of a polymeric chain, which occupies the voids, and hence the gain in strength is maximum. The addition of both nano-Fe_2O_3 and CLS creates a more dense structure. With the addition of CLS, there is a reduction in negatively charged clay surfaces with positively charged CLS [28]. Figure 7d depicts 0.2% nano-Fe_2O_3 blended with 3% CLS and shows a decrement in strength as the polymer chain formed by the nanosoil matrix and CLS particles disintegrates with the addition of CLS or nano-Fe_2O_3 beyond the optimum. Soil particles amalgamate with CLS and nano-Fe_2O_3, but in some portions, excessive stabilizers will accumulate, increasing the soil's porosity. This increase in the porosity will lead to a reduction in strength.

4 Conclusions

In the current study, the combined effect of incorporating nano-Fe_2O_3 and CLS in enhancing the compaction and strength characteristics of a high plastic clay is investigated. The following conclusions are drawn from the study:

- With an increase in nano-Fe_2O_3, LL showed a decrement of 9%, and PI exhibited a decrease of 27%.
- Compaction studies revealed that a notable decrease in optimum moisture content followed by a corresponding increase in maximum dry density was achieved when the clay was blended with 0.2% nano-Fe_2O_3 and 2% CLS.
- Irrespective of the dosage of nano-Fe_2O_3 and CLS, the UCS values increased with an increase in the curing period. The optimum dosage of nano-Fe_2O_3 and CLS was found to be 0.2% and 2% respectively which resulted in a 170% increase in compressive strength at the end of 28 days of the curing period. This increase is attributed to the formation of polymeric chains between nano-Fe_2O_3 and clay particles in the presence of CLS.
- The scanning electron microscopic images revealed a closely packed crystal structure with reduced pore spaces confirming the interaction mechanism responsible for the increase in unconfined compression strength.

This study has corroborated the fact that when nano-Fe_2O_3 is blended with CLS, it can enhance the strength characteristics of high plastic clay. Moreover, the production cost of selected nanomaterials can be reduced with their widespread utilization. Nanomaterials require relatively lower binder dosages compared to other compounds owing to their small size and larger specific surface area.

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Effect of Granite Sand and Calcium Lignosulphonate on the Shrinkage Characteristic of Clay

Gudla Amulya and Arif Ali Baig Moghal

1 Introduction

Clays are inherent materials that are predominantly composed fine grained minerals which are responsible for the volume change when subjected to water and are site specific. These clays exhibit poor performance in terms of shear strength, compressibility, shrinkage and swelling [12, 19]. Addressing to these challenges, the geotechnical engineers have come up with several solutions that enhance the performance poor soils. Chemical stabilization is one of the ground improvement techniques which is pronouncing rapidly for its superior outcomes. Additives like cement [22], lime [11], magnesium chloride [34], phospho-gypsum [35], etc., are used to improve the properties of weak soils. Despite their workability, they are limited by a high pH of groundwater, expansion in production as per requirement, economic issues, and environmental issues like CO_2 emissions [19]. These issues led to the exploration of sustainable alternatives having lower greenhouse gas emissions like biopolymers for expansive clay [8], lignosulphonates for erodible soil [32], calcium carbide residue for clays [19], fly ash and slag for recycled demolition aggregates [6]. These studies showed that the type of soil, dosage, chemical chain formed affect the competence and outcome of the process for respective problems.

Volumetric shrinkage is the parameter that affect the soil and structure upon drying and affects the performance of clay soil under atmospheric conditions [30]. Shrinkage Limit (Ws) is the limiting moisture content at which further reduction in moisture will not cause any decrease in the volume of soil mass. It is the state of soil which

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describes the pore space that present in soil after it has been allowed to compact itself to the maximum density obtainable by shrinkage. The triangular arrangement of the particles is considered as one of the best arrangements of the particles. The attractive and repulsive force fields are uniformly distributed in the obtained geometrical configuration, with no structural severance [16]. This parameter is assessed by shrinkage limit. Some of the works related are, Sivapullaiah et al. [27] worked on lime stabilization of clays where the optimum content of lime required for clay is 6%. The shrinkage limit of kaolinite and montmorillonite increased with lime up to some extent irrespective of clay mineral. Azzam [7] worked on the polymer to create nanocomposites in the soil to improve the shrinkage property of that soil. The range of polymer dosage is 0–15%. He observed that increased polymer content reduced the volumetric strain of the dry pat. Vydehi et al. [33] worked on the shrinkage of the biopolymer treated soil and concluded that biopolymer treatment on low plastic clay leads to curling and desiccation cracking. An investigation is done on a thin layer of clay that is subjected to shrink and examined the occurrence of desiccation cracking which is followed by vertical subsidence. This work also examined the crack length, crack propagation, and crack intersections formed on the dry clay pat [30]. A swell-shrink study is done on compacted expansive clay stabilized with lime. The lime dosage ranges from 0 to 4%. It is concluded that the samples prepared at OMC and less than optimum lime content (OLC) show less swelling pressure with an increase in lime content [1]. Though, many stabilizers are existing to address the volumetric shrinkage and cracking, the works are still limited to the dosage of the additive and its occurrence. This led to the exploration of better additives to overcome the limitations. The current study focuses on stabilization of clay against shrinkage by using granite sand (GS) and calcium lignosulphonate (CLS).

GS is a waste by-product obtained from the aggregate crushing industry. It is considered for consumption because it has a similar mineral composition to sand and is regarded as an industry by-product formed during the crushing process, which increased the utilization possibilities [4, 17]. GS was used as a secondary stabilizer for a BC soil mixed with lime. Addition of this inert material improved the index properties of the soil [20]. Ogbonnaya and Illoabachie [24] used granite dust to stabilize Abakaliki clays and observed an improvement in the index and engineering properties. Kufre Etim et al. [18] used micro-sized granite dust particles to stabilize a disturbed laterite soil added with cement. They observed an increase in California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) at 6% cement and 8% quarry dust. A study was made on stabilizing black cotton soil with quarry dust by different compactive efforts to know the effect on compaction attributes and CBR [23]. Mudgal et al. [21] studied the binary effect of lime and stone dust on the engineering properties of black cotton soil. Chetia and Sridharan [10] reviewed on the effect of quarry dust on different properties of different soils.

Lignosulphonates are obtained from the wood and paper industry after sulfite pulping of the soft wood [29]. The type of lignosulphonate is obtained from the extraction process of the complex polymer [5, 25]. It is a nontoxic admixture that stabilizes cohesive and cohesionless soils. Since the quantity to be used is very less, the effect of leaching on groundwater chemistry is very less or negligible [32].

Alazigha et al. [2] stated that 2% addition of CLS is required to decrease the swell potential of the remolded expansive soil. Silty sand and dispersive clay were treated with 0–0.6% CLS dosages where the residual strength of silty sand is increased with an increase in dosage of CLS [9]. An expansive soil in China is stabilized using CLS to improve its durability property [15].

The significance of using these stabilizers is their enormous availability at low cost with zero carbon footprint. The authors tried to improve the locally available clay with different dosages of GS and CLS. Many studies are conducted on the effective use of GS alone, CLS alone, or in combination with GS and other additives to treat various types of soil, but no comparisons have been made with an inert material (GS) and a non-traditional additive (CLS) individually on clay and the combination. This work unveils the effect of GS, CLS, and GS-CLS at different dosages of each on shrinkage of clay soil.

2 Materials

2.1 Clay

The soil is collected from the Hanamkonda region of Telangana State. It is a remolded soil collected at 3 ft depth from the ground level. The soil is tested for index and engineering properties. Table 1 shows the characterization of clay.

Table 1 Physico-chemical and index properties of clay

Properties	Results
Color	Grayish black
Specific gravity	2.6
Liquid limit (%)	45
Plastic limit (%)	22
Plasticity index (%)	22
Shrinkage limit (%)	13
Fines (%)	59
IS classification	CI
Differential free swell (%)	33
pH	7.7

Table 2 Physical, chemical, and index properties of GS

Properties	Results
Color	Gray
Specific gravity	2.72
Sand fraction (%)	90
Coarse sand (%)	19
Medium sand (%)	32
Fine sand (%)	39
Mean particle size (μ)	600
IS classification	SM-SP
pH	7.36

2.2 GS

It is collected from Rampur village in Telangana. The collected GS is tested for its characterization according IS codal provisions. This typical GS bears the properties shown in Table 2.

2.3 CLS

CLS is a fine powder which exhibits hydrophilic phenomenon. Table 3 shows the typical characteristics of CLS.

3 Sample Preparation

Studies were conducted by varying GS content in the range of 30, 40, and 50% dosages at a defined volume. Each sample is denoted as 7C3G (70% clay and 30% GS), 6C4G (60% clay and 40% GS), and 5C5G (50% clay and 50% GS). The selected dosages are according to Soosan et al. [28]. The CLS dosages are 0.5, 1, 1.5, and 2% dry weight of clay-GS mix. Studies from Chen and Indraratna [9], Alazigha et al. [2, 3] the maximum dosage of CLS required to stabilize the soil is 6%. As the selected

Table 3 Physical and chemical properties of CLS

Properties	Results
Color	Yellow brown
Molar mass	528.61 g/mol
pH	4.3
Solubility	Soluble in water