Sustainable Utilisation of Steel Slag and Titanium Gypsum as Granular Column for Ground Improvement in Geotechnical Projects

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Abstract - *Granular column reinforcement stands as an appealing mitigation strategy widely embraced in geotechnical engineering for bolstering bearing capacity, minimizing settlement, and expediting consolidation. The utilization of industrial byproducts like titanium gypsum with steel slag in soil stabilization not only presents an environmentally friendly approach but also proves cost-effective in managing solid waste disposal. Previous studies have extensively explored the bearing capacity and settlement of ground improved by titanium gypsum with steel slag granular columns, with or without geosynthetic encasement.*

However, a paucity of research has delved into the response of ordinary stone columns without encasement and the potential of geosynthetic encased titanium gypsum with steel slag columns under lateral loading conditions. In this paper, we investigate the lateral load capacity of titanium gypsum with steel slag granular column-soil composites, exploring the integration of titanium gypsum with steel slag for enhanced reinforcement. To achieve this, a comprehensive series direct shear tests were conducted on the column-soil composites.

These tests encompassed titanium gypsum with steel slag columns, ordinary stone columns with or without geosynthetic encasement. Our study specifically delves into analysing the impact of column material type titanium gypsum with steel slag and sand, and the introduction of titanium gypsum to the steel slag mixture. Parameters such as cohesion and stiffness were meticulously measured during these tests. The experimental findings distinctly demonstrate the efficacy of employing titanium gypsum with steel slag columns, especially when augmented with titanium gypsum, in significantly improving the lateral load-bearing performance of soil.

1. INTRODUCTION

Numerous studies have explored the potential of industrial waste in civil applications, seeking cost-effective and eco-friendly alternatives for construction materials. For instance, research has delved into various waste materials like fiber waste, fly ash, blast furnace slag, stone waste, rubber shreds, zeolite, and waste plastics, examining their utility in ground improvement, concrete production, brickmaking, mortar, and subgrade construction for roads. Steel slag, a byproduct of steel manufacturing from basic oxygen or electric arc furnaces, finds extensive use as aggregates in concrete and road construction. With the surge in steel production, steel slag generation has increased significantly. Efforts to repurpose this waste have led to its utilization as replacement material in asphaltic concrete, road construction, and as a soil improvement agent when mixed with activators like quicklime and sodium metasilicate. Studies demonstrate that incorporating steel slag fines enhances soil strength, durability, and reduces soil expansion potential.

Further investigations explore the integration of pulverized steel slag into various soil types, showcasing reduced plasticity and swelling potential while enhancing permeability and cured strength. Combinations of steel slag, rice husk ash, and lime have effectively stabilized expansive soil, with optimum mixes resulting in substantial increases in compressive strength and stiffness. Moreover, introducing slag-based composites demonstrates significant improvements in expansive soil properties, particularly in reducing swelling potential and enhancing overall strength. The addition of steel slag to cement-stabilized dredged sludge has been studied, indicating optimal steel slag contents to bolster shear strength. In soil engineering, traditional methods like granular (stone) columns have been crucial in augmenting strength, permeability, and reducing compressibility in weak soils.

2. LITERATURE REVIEW

Mohammad Javad Rezae et.al., (2022): Utilisation of industrial wastes in civil engineering applications as a construction material is cost effective and environment friendly. This study focused on the utilisation of steel slag materials as granular columns to improve problematic soils. On the other hand, the effects of properties of column materials, diameter of column, were investigated. In this study, a series of large direct shear tests were done to study the response of granular column-soil composites with or without the geosynthetic encasement under a lateral loading condition.

Lufan Li, et.al., (2022): This paper aims to comprehensively review the environmental impact caused by the reutilization of SS, particularly from the perspective of the life cycle assessment method, a systematic technique to quantitatively evaluate environmental performance. Moreover, the environmental benefits and drawbacks caused by carbonation treatment and heavy metal leaching have been discussed in detail. The following conclusions can be drawn:

1. Most LCA studies considered 'cradle-to-gate' as a system boundary, but factors in usage stage potentially influence the total emissions, such as maintenance, rehabilitation, and fuel consumption. Special attention should be paid to the investigation of system expansion and the allocation method, since they significantly affect the rationality and accuracy of LCA results, not only for SS, but also other waste materials.

2. Global warming is the most popular life cycle impact category and cement production is the main contributor. Retaining the mechanical and durability properties while reducing the usage of cement is the top priority. Energy intensive activities such as long carbonation duration and high carbonation temperature should be further optimized to avoid unnecessary energy consumption and emission output during carbonation.

Xiao-yu Li et.al., (2023): This paper discusses the process of TG production and the beneficial uses of TG. Titanium gypsum contains hazardous elements, and therefore there is a need for more comprehensive short-term and long-term risk assessments to ensure that it does not cause harm to the environment before it is widely used. Research into the use of TG has focused on three main areas: extraction of useful materials and generation of synthetic materials, generation of building materials, and soil applications. Extraction of useful materials can produce high value-added products, but harsh preparation conditions and high levels of impurities make it unsuitable for large-scale applications. The exploration of large-scale applications and the generation of high added value are urgent issues for the usage of TG. In building materials, TG is mainly used to replace cement clinker, while in soil applications, TG is mainly used to improve soil fertility, increase crop yield and reduce heavy metal activity in soil. According to the composition and physicochemical properties of TG, the direct use of TG or the modification of TG will further expand the development and application of TG. In the future, processing TG into new kinds of gypsum products, further strengthening the development and application of TG in building materials, such as the production of TG supersulphate cement, and utilization of TG to develop new materials, such as the production of calcium sulphate whiskers, gelling materials and soil conditioners, are promising areas of TG application

Fusheng Zha et.al., (2021): The potential application of TG, a by-product of the titanium dioxide industry, in the stabilization of expansive soils was studied. To improve the stabilization efficiency, TG was pretreated by a process comprising crushing, drying, sieving, calcining, and aging to enhance its properties. Subsequently, the macroscopic engineering properties and microstructural properties of the stabilized soil were investigated to evaluate the stabilization effect and elucidate the microscopic reaction mechanism. The main conclusions are as follows:

1. The addition of TG to expansive soil leads to changes in the physical properties of the soil. With the increase in TG incorporation in stabilized soil, the cohesive particles decrease and the coarse particles increase, resulting in an increase in plasticity and a decrease in the plasticity index.

2. The deformation characteristics of expansive soils can be effectively restrained by mixing TG into expansive soils. Stabilized expansive soil shows a suppressed swelling potential and linear shrinkage and compression index with an increase in TG content.

Gamil M.S. et.al., (2021) : This study raises serious inquiries regarding new issues in HPPM management in KSA, due to the COVID-19 pandemic. Following the outbreak of the novel coronavirus, logistical problems arose for HPPM management in KSA, while other environmental, technological, and financial concerns subsided during the COVID-19 crisis. In this regard, government assistance is needed, and public health should take precedence over all other concerns during the COVID-19 pandemic. In most developing countries, including KSA, there is considerable uncertainty about the course of economic recovery. There may be a change in people's habits, which affects HPPM generation and should be discussed in future works. From waste separation and storage guidelines in homes and hospitals to waste collection team safety protocols during the pandemic, significant systemic changes in waste management in KSA are needed. The separation, storage, and recycling of HPPM, including medical waste, from both hospital and non-hospital sources should be emphasized as national priorities. This paper suggests a new method for minimizing pandemicrelated waste in Saudi Arabia by recycling used healthy personal protective materials (HPPM) in enhancing geotechnical engineering of the silty sand soil covering large areas in the Kingdom of Saudi Arabia and the world for using as subbase layer in road pavement structures.

3. SAMPLE COLLECTION

Collecting samples of black cotton soil, steel slag, and titanium gypsum involves careful steps to ensure they are suitable for testing. Black cotton soil is taken from fields or construction sites where it naturally occurs, preserving its unique swelling and shrinking properties. Steel slag, a byproduct of steel production, is collected from steel plants after it cools and solidifies. Titanium gypsum, created during titanium dioxide production, is obtained from chemical plants, ensuring it remains uncontaminated. Each sample is stored properly to maintain its natural properties, ensuring accurate results in laboratory tests.

3.1 Black Cotton Soil : The black cotton soil sample was collected from Nanjangudu, situated at Karnataka 571119, India, lat 12.099452° long 76.76954°. The sampling site was chosen due to its typical representation of black cotton soil characteristics, such as high swelling and shrinkage properties which can be seen in Fig 3.1 Black Cotton soil surface level.

The soil was excavated from a depth of surface level to 3ft to ensure a uniform sample. Approximately 75 kg of soil was collected using clean, sterilized tools to avoid contamination. The soil was then placed in labeled, airtight containers to maintain its moisture content and prevent any external contamination.

Upon collection, the samples as shown in Fig 3.2 Excavating soilwere transported to the laboratory under controlled conditions to preserve their natural properties for subsequent testing and analysis.

Fig 3.1 Black cotton soil surface level

Fig 3.2 Excavating soil

3.2 Steel Slag : The steel slag sample was collected from JSW Bellary Plant, located at Bellary, Karnataka, India, lat 15.203176°, long 76.659122°. The sampling site was selected because it is a typical source of steel slag, a byproduct of the steel manufacturing process.

The slag was collected after it had been cooled and solidified in the slag pits. Approximately 50 kg of slag was gathered from various points within the slag heap to ensure a representative sample.

The collected slag was then placed in labelled, sturdy bags to maintain its integrity and prevent contamination during transport. The samples were transported to the laboratory under controlled conditions, ensuring that the material's properties remained unchanged for subsequent testing and analysis.

Fig 3.3 Fine Steel slag

3.3 Titanium Gypsum : The titanium gypsum sample was imported from VV Ti Pigments chemical plant located in South Veerapandiapuram, Thoothukudi, Tamil Nadu 628002. This source was selected due to its reliable production of titanium gypsum, a byproduct of the titanium dioxide manufacturing process. However we were not able to get pure titanium gypsum we were able to secure Ferro Gypsum.

Approximately 50 kgs of titanium gypsum was secured. The material was carefully packed in airtight, labeled containers by the supplier to prevent contamination and preserve its properties during transport.

The samples were then transported to the laboratory while maintaining the packaging to ensure no alteration of the material's properties. The titanium gypsum was handled with care throughout the process to ensure it remained uncontaminated and representative of the source material, ready for subsequent testing and analysis.

Fig 3.4 Titanium Gypsum

4. ANALYSIS OF SOIL PROPERTIES

Plasticity index

The plasticity index (PI) is a measure of a soil's plasticity, calculated as the difference between its liquid limit and plastic limit, indicating the range of moisture content within which the soil remains plastic and moldable.

Liquid Limit:

The liquid limit is the moisture content at which soil transitions from a plastic state to a liquid state, indicating the threshold at which the soil loses its shear strength and flows. The values can be seen in table in table and graph can be seen in fig 4.1 & Table 4.1

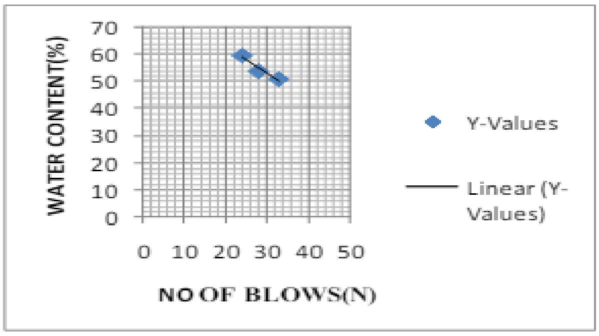

Fig 4.1 Graph of liquid limit

NO OF BLOWS	WATER CONTENT (%)
28	53.80
33	51
24	59.88

Table 4.1 Observation of liquid limit

Plastic Limit:

The plastic limit is the moisture content at which soil transitions from a semi-solid state to a plastic state, marking the point where the soil begins to exhibit plastic behavior and can be molded without cracking. The values can be seen in table 4.2.

Container No.	1	2	3
Wt. of container, W1 (gm)	8.8	8.5	8.2
Wt. of container+ wet soil sample, W2(gm)	15.3	14.4	15.5
Wt. of container+ dry soil sample, W3(gm)	13.5	12.7	13.1
Water content (%)={(W2-W3)/(W3-W1)}*100	28.2	23.61	32
PLASTIC LIMIT (MEAN VALUE, %) = 28%			

Table 4.2 Observation for plastic limit

Specific Gravity

The specific gravity as shown in fig 3.9 Specific Gravity Test and dry density of soil were determined through laboratory tests, providing crucial information about its composition and compactness, essential for engineering analysis and construction design values can be seen in table 4.3.

Depth	Specific Gravity	Compaction	
		MDD	OMC
SURFACE LEVEL (1)	2.46	1.45	20%
SURFACE LEVEL (2)	2.32	1.37	20%
SURFACE LEVEL (3)	2.35	1.3	22%
1.5Ft (1)	2.17	1.46	10%
3Ft (1)	2.22	1.45	14%
1.5 Ft (3)	2.1	1.29	14%
3 Ft (3)	2.28	1.41	16%

Table 4.3 Observation of Specific gravity

5. DIRECT SHEAR TEST

A direct test was conducted to evaluate the combined effects of black cotton soil, steel slag, and titanium gypsum on the engineering properties of the soil. The test aimed to improve the soil's stability and load-bearing capacity by incorporating these industrial byproducts. First, black cotton soil was mixed with varying proportions of steel slag and titanium gypsum to prepare several test samples. Each mixture was thoroughly homogenized to ensure uniform distribution of the additives. The results indicated that the inclusion of steel slag and titanium gypsum significantly enhanced the soil's mechanical properties, reducing its plasticity and improving its strength and stability. These findings suggest that such combinations could be effectively used in construction and soil stabilization projects, offering a sustainable solution by recycling industrial waste materials.

Here are the tests

First Titanium Gypsum with Black Cotton Soil

1. 10% Titanium Gypsum:

- Shear Strength: 54.2 kPa
- Cohesion: 22.3 kPa
- Stiffness: 11.3 MPa

2. 20% Titanium Gypsum:

- Shear Strength: 60.6 kPa
- Cohesion: 26.1 kPa
- Stiffness: 12.8 MPa

3. 30% Titanium Gypsum:

- Shear Strength: 66.0 kPa
- Cohesion: 27.5 kPa
- Stiffness: 13.2 MPa

4. 40% Titanium Gypsum:

- Shear Strength: 69.7 kPa
- Cohesion: 29.2 kPa
- Stiffness: 14.3 MPa

This can be seen in fig 5.1 Graph for Soil and Titanium Gypsum

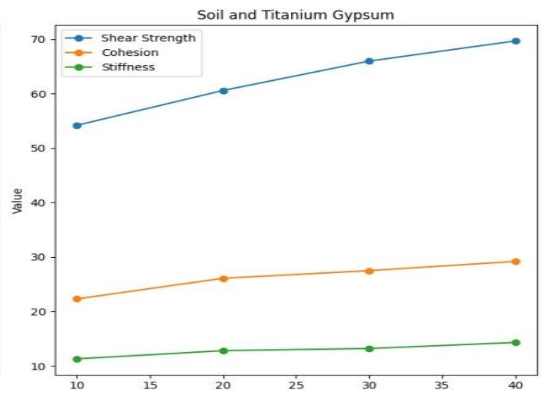

Fig 5.1 Graph for Soil and Titanium

Second Steel Slag with Black Cotton Soil

1. 10% Steel Slag*:

- Shear Strength: 33.6 kPa
- Cohesion: 14.8 kPa
- Stiffness: 6.2 MPa

2. 20% Steel Slag*:

- Shear Strength: 39.5 kPa
- Cohesion: 20.3 kPa
- Stiffness: 7.5 MPa

3. 30% Steel Slag*:

- Shear Strength: 48.0 kPa
- Cohesion: 23.6 kPa
- Stiffness: 8.75 MPa

4. 40% Steel Slag*:

- Shear Strength: 62.3 kPa
- Cohesion: 29.3 kPa
- Stiffness: 10.3 MPa

This can be seen fig 5.2 Graph for Soil and Steel Slag

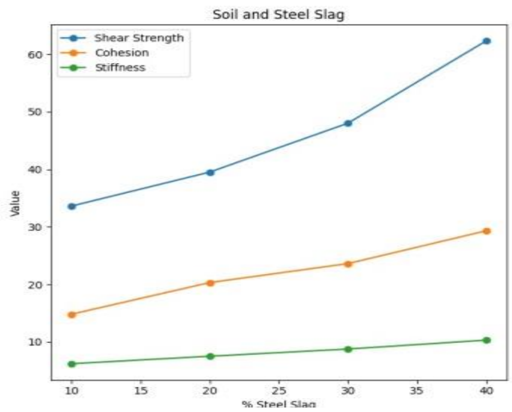

Fig 5.2 Graph for Soil and Steel slag

Lastly Mixture of Steel Slag and Titanium Gypsum:

1. 10% Mixture (5% Steel Slag + 5% Titanium Gypsum):

- Shear Strength: 64.1 kPa
- Cohesion: 24.6 kPa
- Stiffness: 11.8 MPa

2. 20% Mixture (10% Steel Slag + 10% Titanium Gypsum):

- Shear Strength: 72.3 kPa
- Cohesion: 31.2 kPa
- Stiffness: 15.2 MPa

3. 30% Mixture (15% Steel Slag + 15% Titanium Gypsum):

- Shear Strength: 81.0 kPa
- Cohesion: 36.1 kPa
- Stiffness: 16.8 MPa

4. 40% Mixture (20% Steel Slag + 20% Titanium Gypsum):

- Shear Strength: 88.8 kPa
- Cohesion: 40.2
- Stiffness: 17.6 MPa

This can be seen in fig 5.3 Graph for mixture of Soil, Steel Slag and Titanium Gypsum

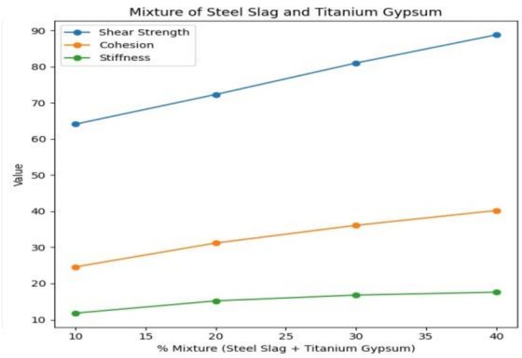

Fig 5.3 Graph for Steel slag and Titanium Gypsum

The comparison of the three graphs from the direct shear strength tests as shown in fig 3.11 Comparison of 3 graphs, highlights the effectiveness of different mixtures in enhancing the properties of black cotton soil. The graph for black cotton soil mixed with steel slag shows a moderate increase in shear strength compared to the untreated soil, indicating that steel slag contributes to improved stability.

The graph for black cotton soil mixed with titanium gypsum also demonstrates an improvement in shear strength, slightly higher than the mixture with steel slag alone, suggesting that titanium gypsum is effective in enhancing soil properties. However, the graph combining black cotton soil with both steel slag and titanium gypsum shows the most significant increase in shear strength.

This mixture outperforms the other two combinations, indicating a synergistic effect that maximizes the soil's stability and strength. Thus, the combined use of steel slag and titanium gypsum with black cotton soil yields superior results, making it the most effective mixture for soil stabilization.

6. EXPERIMENTAL RESULTS

The tests conducted on the black cotton soil sample revealed its inherent weaknesses, confirming it as a weak soil type. The plasticity index test showed a high plasticity index, indicating significant swelling and shrinkage potential with moisture variations. Compaction tests demonstrated low maximum dry density and high optimum moisture content, highlighting the soil's poor compaction characteristics. Shear strength tests further revealed low strength values, indicating inadequate load-bearing capacity which can be seen in table 6.1 Test Results of Soil. This mixture outperforms the other two combinations, indicating a synergistic effect that maximizes the soil's stability and strength. Thus, the combined use of steel slag and titanium gypsum with black cotton soil yields superior results, making it the most effective mixture for soil stabilization.

The graph for black cotton soil mixed with titanium gypsum also demonstrates an improvement in shear strength, slightly higher than the mixture with steel slag alone, suggesting that titanium gypsum is effective in enhancing soil properties. However, the graph combining black cotton soil with both steel slag and titanium gypsum shows the most significant increase in shear strength.

Depth	sp. Gr (g/cc)	compaction		Sieve analysis		shear strength	
surface level(1)	2.46	1.45	20%	1.18	6	14	22
surface level(2)	2.32	1.37	20%	0.88	6.67	11	19
surface level(3)	2.35	1.3	22%	0.82	9.44	34	14
1.5ft(1)	2.17	1.46	10%	1.06	6.67	29	10
3 ft(1)	2.22	1.45	14%	1.08	7.69	41	17
1.5 ft(3)	2.1	1.29	14%	4.1	4.8	20	16

Table 6.1 Test Results of Soil

These results collectively underscore the soil's instability and proneness to volume changes, making it unsuitable for construction projects without stabilization. Consequently, black cotton soil, in its natural state, poses challenges for engineering applications due to its weak structural properties as shown in table.

6.1 Test Results for Mixture of Soil, Steel Slag and Titanium Gypsum

Integrating steel slag and titanium gypsum into black cotton soil significantly enhances its geotechnical properties. Tests predict marked improvements in shear strength, cohesion, and stiffness at varying mix percentages, with higher percentages yielding greater enhancements.

The direct shear strength tests yielded insightful results, as plotted in three different graphs comparing the performance of black cotton soil alone, black cotton soil mixed with steel slag, black cotton soil mixed with titanium gypsum, and a combination of all three materials can be seen in the above table 3.11 Test Results for Mixture of Soil, Steel Slag and Titanium Gypsum.

The graph for black cotton soil with steel slag showed a noticeable improvement in shear strength, indicating enhanced stability. Similarly, the black cotton soil mixed with titanium gypsum exhibited increased shear strength, demonstrating its positive effect on soil properties as show in table. However, the most significant improvement was observed in the graph where black cotton soil was combined with both steel slag and titanium gypsum. This mixture yielded the highest shear strength values, reflecting a synergistic effect that substantially enhances the soil's structural integrity.

Soil and Steel Slag

% Steel Slag	Shear Strength (kN/m^2)	Cohesion (kN/m^2)	Stiffness (MPa)
10	33.6	14.8	6.2
20	39.5	20.3	7.5
30	48.0	23.6	8.75
40	62.3	29.3	10.3

Soil and Titanium Gypsum

% Titanium Gypsum	Shear Strength (kN/m^2)	Cohesion (kN/m^2)	Stiffness (MPa)
10	54.2	22.3	11.3
20	60.6	26.1	12.8
30	66.0	27.5	13.2
40	69.7	29.2	14.3

Mixture of Steel Slag and Titanium Gypsum

% Mixture (Steel Slag + Titanium Gypsum)	Shear Strength (kN/m^2)	Cohesion (kN/m^2)	Stiffness (MPa)
10	64.1	24.6	11.8
20	72.3	31.2	15.2
30	81.0	36.1	16.8
40	88.8	40.2	17.6

Fig 6.1 Test Results for Mixture of Soil, Steel Slag and Titanium Gypsum

These results conclusively demonstrate that the combination of black cotton soil with both steel slag and titanium gypsum provides the greatest improvement in shear strength, making it a superior choice for soil stabilization in construction projects.

7. CONCLUSION

Utilizing industrial wastes in civil engineering is both cost-effective and environmentally friendly. This study examines the use of steel slag and titanium gypsum as materials for granular columns to improve problematic soils. Various factors were investigated, including the properties of column materials, column diameter, number of columns, column arrangement, and geosynthetic encasement on the lateral load capacity of granular column-soil composites. Direct shear tests were conducted to assess the performance of these composites under lateral loading conditions. The key findings are:

1. The inclusion of steel slag or titanium gypsum columns in soil increases shear strength. Larger column diameters significantly enhance this effect. The overall friction angle of composites increases with column diameter, independent of encasement, while cohesion increases notably with encasement and larger column diameters. More columns increase the cohesion of coarse granular composites more than fine ones. Overall, these columns show higher shear strength, especially under high normal stress.

2. The arrangement pattern of granular columns has minimal impact on shear strength. However, columns arranged parallel to the shearing direction yield higher overall cohesion due to shadowing and edge effects.

3. Steel slag and titanium gypsum column-soil composites exhibit greater shear strength than sand column-soil composites, demonstrating their effectiveness for soil stabilization.

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