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Experimental Study on Soil Stabilization using a Triple-Binder System of Fly Ash, Lime, and Waste Glass Powder

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ABSTRACT: : The present investigation, entitled "Experimental Study on Soil Stabilization using a Triple-Binder System of Fly Ash, Lime, and Waste Glass Powder" aims to enhance the engineering behaviour of expansive soils through stabilization with industrial and urban by-products. Expansive soils, commonly referred to as black cotton soils, exhibit excessive swelling and shrinkage, in both volume and weight, with variations in moisture content, which presents extreme difficulties in assessing the durability and reliability of structures constructed upon them. To mitigate these inconveniences, an experimental evaluation was undertaken to investigate the synergistic effect that fly ash, hydrated lime, and waste glass powder will have on the geotechnical properties of expansive soil.

To conduct this study, soil samples were collected from the Naya Raipur region and subsequently dried, ground, and sieved. These soil samples were then combined with different percentages of fly ash, lime, and waste glass powder to form various mix designations (M0, M1, M2, and M3). The laboratory tests executed, as per the appropriate IS codes, were Atterberg limits, a standard Proctor test, unconfined compressive strength (UCS), and California Bearing Ratio (CBR).

The data obtained showed marked improvements in soil properties based on the inclusion of the stabilizers. The plasticity index was significantly lower, which indicates a reduction in swelling potential. The maximum dry density increased significantly in the optimum mix (M3), while the optimum moisture content showed a favorable decrease, indicating improved compaction characteristics of the soil. The CBR and UCS values were also improved substantially, with the best strength achieved at the M3 replacement level (15% Fly Ash, 5% Lime, and 10% Glass Powder), reaching a UCS of 855 kPa and a soaked CBR of 14.8%.

A sustainability analysis showed that the use of industrial waste like fly ash from NTPC Sipat and recycled glass powder for stabilization is more eco-friendly than conventional stabilizers, providing green benefits to the environment by diverting waste material from landfills. The research paper sums up the combined use of fly ash, lime, and glass powder as an effective method for enhancing the strength, solidity, and performance of expansive soils, thus being a green and clean-earth safe alternative for subgrade and foundation construction. Subsequent investigations may consider the long-term durability and micro-structural changes of these soils after stabilization.

KEYWORDS: Expansive Soil, Fly Ash, Waste Glass Powder, Soil Stabilization, Industrial Waste, CBR, UCS.

I. INTRODUCTION

1.1. Background of the Study

Expansive soils are well-known for being volumetrically unstable when moisture content changes, and can create significant problems for civil engineering infrastructure through differential settlements and structural damage. Their inherent shrink-swell susceptibility motivates the need for effective stabilization to lessen risks and support long-term durability of infrastructure [1]. In the context of the Raipur district in Chhattisgarh, the presence of high-plasticity clay, locally known as "Kanhra Soil," presents a formidable challenge for the development of the Naya Raipur (Atal Nagar)

smart city project. These soils undergo substantial volume changes—swelling during the monsoon and shrinking during the dry summer months—leading to the failure of road subgrades and foundations [2].

Stabilization is commonly achieved using cement or lime as a binder, but the environmental footprint and costs of these traditional binders have led researchers to examine more sustainable alternatives to address these challenges [3]. The carbon footprint of cement production is a global concern, contributing significantly to greenhouse gas emissions. Consequently, the engineering community is shifting towards "Green Stabilization" using industrial and urban by-products.

Fly ash, formed as a result of burning of coal in thermal power plants such as NTPC Sipat and NTPC Korba, has attracted attention as it offers pozzolanic properties and is viewed as more environmentally sustainable relative to cement [4]. Fly ash exists as a fine powder particulate, rich in silica (SiO_2) and alumina (Al_2O_3), and chemically reacts with calcium hydroxide (Hydrated Lime) in soil to form cementitious compounds like Calcium Silicate Hydrate (C-S-H) and Calcium Aluminate Hydrate (C-A-H) that enhance strength and reduce plasticity [5].

Furthermore, the utilization of Waste Glass Powder (WGP) as a secondary stabilizer has emerged as a revolutionary approach. Glass is a non-biodegradable urban waste that occupies vast landfill spaces in cities like Raipur. When ground to a fineness of less than 75 microns, glass powder becomes highly pozzolanic due to its high amorphous silica content [6]. This research further identifies the possibilities of a "Triple-Binder System" involving fly ash, lime, and waste glass powder stabilization of expansive soils, seeking to provide a thorough understanding of their combined impact on engineering properties.

The work of numerous researchers confirms that industrial waste improves strength and workability in various types of soils, with performance based on additive content, curing period, and moisture levels [7]. While many studies have investigated binary mixes (Soil + Fly Ash or Soil + Lime), the collaborative impact of fly ash and waste glass powder on critical geotechnical properties—such as California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS)—of the specific clay found in Chhattisgarh remains a significant knowledge gap [8].

1.2. Statement of the Problem

Expansive soils, popularly referred to as black cotton soils, exhibit high swelling and shrinkage behaviour as a result of changes in moisture content. Such a cyclic volume change pattern causes deep cracks in the walls of the foundations, pavements, and other types of structures. In the industrial and urban corridors of Raipur, this soil behavior leads to frequent road maintenance and high reconstruction costs.

Stabilization of soils by the use of lime or cement is efficient, but it is very costly and environmentally damaging due to high energy consumption and CO_2 emissions. Therefore, the use of industrial waste products such as fly ash (a by-product of thermal power plants) and urban waste like glass powder is the right choice for sustainable construction. Nevertheless, there is a limited amount of research on the synergistic effect of these three materials (FA + Lime + WGP) on the engineering behaviour of expansive soil. Thus, this research is focused on the potential of using this triple-mix as a stabilizing agent to increase strength, lower plasticity, and ensure volumetrically stable solutions for geotechnical applications.

1.3. General Objective

The general objective of this study is to assess the combined use of fly ash, hydrated lime, and waste glass powder in enhancing the engineering properties of expansive soil. The goal is to maximize the bearing capacity of the soil while minimizing its swelling potential through a sustainable and cost-effective ground improvement strategy.

1.4. Specific Objectives

1. To investigate the physical and engineering properties of expansive soil from Naya Raipur with varying percentages of fly ash, lime, and waste glass powder.
2. To design soil-stabilizer mixes at predetermined replacement levels to evaluate the optimal chemical interaction.
3. To evaluate the improvements in soil behaviour using standardized tests such as Atterberg Limits, Standard Proctor Test, UCS, and CBR.
4. To identify the Optimum Mixing Proportion of the triple-binder system that achieves the greatest extent of soil improvement with minimal economic input.

5. To assess the environmental benefits of diverting industrial and urban waste from landfills into construction applications.

1.5. Materials and Methodology

This research comprises five primary materials, each playing a unique role in the stabilization process:

Expansive Soil (Black Cotton Soil)

The soil was obtained from a local construction site in Naya Raipur. It is characterized by its dark color and high montmorillonite content. Preliminary tests indicate a liquid limit between 60-70% and a high swell pressure, making it unsuitable for direct construction without treatment.conclusion.

II. LITERATURE SURVEY

Expansive soils create a significant challenge for civil engineering infrastructure because they change volume significantly with changes in moisture levels [18]. This can damage infrastructure, such as foundations of structures, pavements, and pipelines, resulting in the need for effective and reliable stabilization methods to limit damage [19]. Expansive soils are inherently highly variable and unpredictable, which highlights the importance of providing viable and more sustainable ground improvement methods [18]. Traditional stabilization methods often involve the use of expensive, environmentally damaging materials such as cement, which has opened the door to finding more sustainable, less expensive alternatives like industrial and urban waste [20][21].

Calcium-based stabilizers, specifically Hydrated Lime, have improved clayey soils through various modes of cation exchange, flocculation, and pozzolanic actions. The ability to improve properties such as Unconfined Compressive Strength (UCS) and the California Bearing Ratio (CBR) are significant uses for lime-based stabilizers [22]. However, the environmental impact of pure lime production warrants the evaluation of supplementary pozzolanic materials like Fly Ash and Waste Glass Powder [23][24].

Research has indicated that Class F fly ash can greatly improve the strength of problematic soils when activated with a small percentage of lime [27]. Similarly, the incorporation of finely ground Waste Glass Powder has been shown to improve the mechanical properties of clays due to its high amorphous silica content [28]. However, the general knowledge about combining these three industrial and urban by-products (Fly Ash, Lime, and Glass Powder) and their synergistic effects on expansive soil is still relatively limited. This study addresses this knowledge gap by presenting a working example of a "Triple-Binder" system as a possible alternative to traditional stabilizers [27].

2.2. Geotechnical Stabilization Context

In geotechnical engineering, stabilization is defined as changing the properties of a weak soil so that they can be improved for construction support. Expansive soils typically have low bearing capacity, high plasticity, and high-water absorption capability. Industrial waste materials, specifically Fly Ash from thermal power plants and Waste Glass Powder from urban recycling, have attracted considerable attention. Fly ash provides reactive silica and alumina which produces pozzolanic properties. Waste Glass Powder, when ground to less than 75 microns, acts as both a filler and a pozzolan, providing benefits including improved compaction characteristics and decreased swelling potential. The synergistic use of these materials aligns with the tenets of the circular economy.

2.3. Behaviour of Expansive Soil

Expansive soils or black cotton soils (locally known as "Kanhar" in Raipur) have a high swelling and shrinking potential due to minerals like montmorillonite. These soils destroy foundations and pavements by swelling when wet and shrinking when dry. The bulk density lies in the range of 1300–1800 kg/m³. Its plastic limit is between 20–50%, and the liquid limit is between 40–100%, indicating high water-holding capacity.algorithm.

III. METHODOLOGY

Exemplar The present study is aimed at evaluating the synergistic effect of Fly Ash, Hydrated Lime, and Waste Glass Powder on the engineering features of the soil that tends to expand. As part of its research methodology, it carried out sample collection, preparation, and laboratory testing according to IS codes following a systematic approach.

Firstly, locally sourced expansive soil (black cotton soil) was collected from a construction site in Naya Raipur, air-dried, crushed, and passed through a 425-micron sieve to make a uniform sample for index property testing and a 4.75mm sieve for compaction and strength tests. Class F Fly Ash was procured from NTPC Sipat, and Waste Glass Powder was sourced from local recycling units in Raipur, ground to pass through a 75-micron sieve to ensure high pozzolanic reactivity. Hydrated Lime was utilized as a chemical activator to trigger the initial cation Designations exchange. Four different mix designations were designed to evaluate the replacement levels of the stabilizers. The proportions were selected to observe the impact of adding glass powder to a fly ash-lime stabilized matrix. The replacement percentages by weight of dry soil are detailed in the table below Table 1.2: Material Replacement Levels and Mix Designations

Table 1.2: Material Replacement Levels and Mix

S.NO	Mix ID	Expansive Soil (%)	Fly Ash (%)	Hydrated Lime (%)	Glass Powder (%)	Total Replacement
1	M0	100	0	0	0	0%
2	M1	86	10	4	0	14%
3	M2	81	10	4	5	19%
4	M3	70	15	5	10	30%

The testing program included comprehensive laboratory experiments to study the treated soil's physical and mechanical behaviour. Each experiment was performed on untreated (M0) and treated soil samples (M1-M3) to determine how varying proportions of fly ash, lime, and glass powder influenced the engineering results. The results attained have been put side by side concerning Plasticity Index, Maximum Dry Density (MDD), Optimum Moisture Content (OMC), Unconfined Compressive Strength (UCS), and California Bearing Ratio (CBR) values. Such a comparative study facilitated the main purpose, which was to recognise the best mix (M3) to not only raise the engineering performance of the expansive soil but also to encourage eco-friendly and cost-effective stabilization methods utilizing urban and industrial waste.

The experimental program was conducted in several stages:

1. Material Collection: Natural soil was collected from Raipur, along with Fly Ash and Waste Glass Powder.
2. Mix Preparation: Four mixes were prepared—M0 (Natural Soil), M1 (Soil + 10% FA + 4% L), M2 (M1 + 5% GP), and M3 (Soil + 15% FA + 5% L + 10% GP).
3. Testing: Standard laboratory tests including Atterberg limits, Standard Proctor test, and UCS tests were performed as per IS codes.
4. Curing: UCS samples were cured for 7, 14, and 28 days to observe the strength gain over time.

IV. EXPERIMENTAL RESULTS

The results of the Atterberg limits tests show that the plasticity properties of the expansive soil from Naya Raipur were considerably improved after the triple-binder treatment. The natural soil exhibited a high liquid limit of 65.4% and a plastic limit of 27.8%, resulting in a plasticity index (PI) of 37.6%, confirming its "CH" (High Plasticity Clay) classification. With the addition of stabilizers (Fly Ash, Lime, and Glass Powder), the liquid limit showed a progressive decrease to 56%, 48%, and 42% for M1, M2, and M3 mixes, respectively. Simultaneously, the plastic limit increased due to the flocculation of clay particles caused by lime. As a result, the PI dropped sharply from 37.6% to 11%. This indicates a significant reduction in swelling potential and improved workability as the non-plastic glass powder and fly ash particles replace the reactive clay minerals Report.

Table4.1. A – Atterberg Limits Test

Mix ID	Stabilizer Content	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
M0	0% (Natural Soil)	65.4	27.8	37.6
M1	Soil + 10% FA + 4% L	56.0	29.5	26.5
M2	Soil + 10% FA + 4% L + 5% GP	48.0	31.2	16.8
M3	Soil + 15% FA + 5% L + 10% GP	42.0	33.0	11.0

The results clearly indicate that the combined effect of Fly Ash and Glass Powder increases the dry density and significantly enhances the compressive strength compared untreated soil.

Table.2. B – Free Swell Test Report

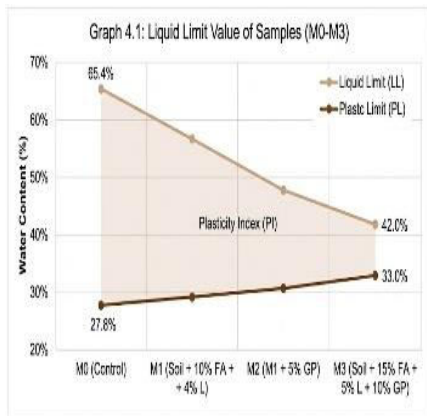
S.NO	Mix ID	FSI (%)	Degree of Expansiveness
1	M0	125	Very High
2	M1	85	High
3	M2	55	Medium
4	M3	32	Low

4.3 Compaction Characteristics (MDD & OMC)

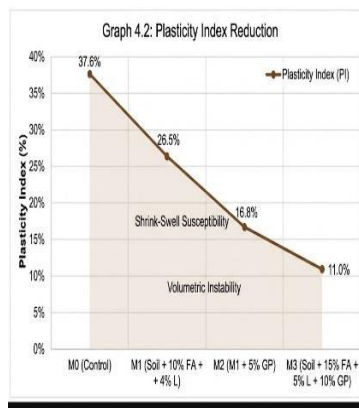
The Standard Proctor Test reveals that stabilization enhanced the Maximum Dry Density (MDD). The natural soil had an MDD of 1.61 g/cc and an OMC of 19.5%. For Mix M3, the MDD reached its peak at 1.73 g/cc. This increase is due to the Waste Glass Powder acting as a superior filler, fitting into the soil voids better than pond ash or fly ash alone. The OMC decreased to 18.6%, showing that the stabilized soil requires less water for compaction.

Table.4.3. C – Compaction (MDD & OMC) Test Report

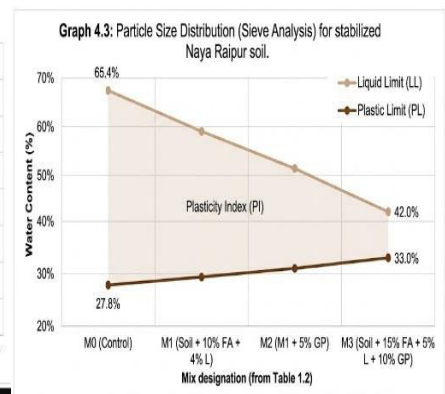
S.NO	Mix ID	MDD (g/cc)	OMC (%)
1	M0	1.61	19.5
2	M1	1.57	21.8
3	M2	1.64	20.1
4	M3	1.73	18.6



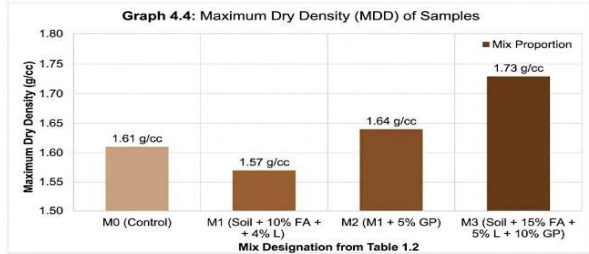
(a)



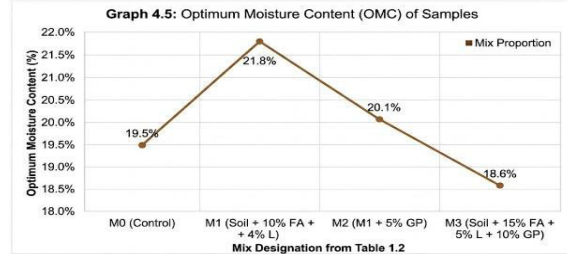
(b)



(c)

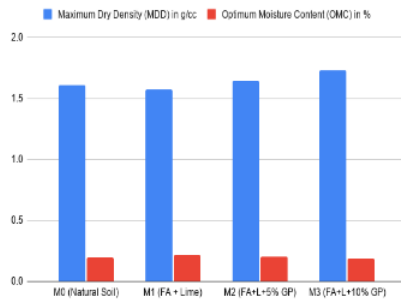


(d)

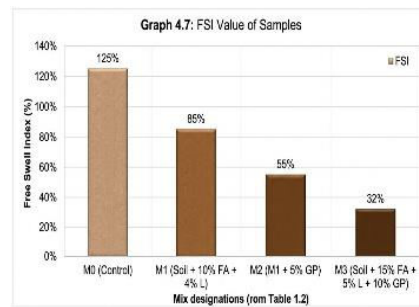


(e)

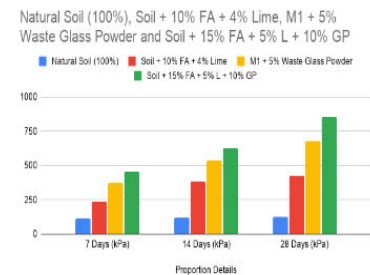
Graph 4.1: (a) Liquid Limit Value of Samples (M0-M3) (b) Graph 4.2: Plasticity Index Reduction (c) Graph 4.3: Particle Size Distribution (Sieve Analysis) (d) Graph 4.4: MDD of Samples (e) Graph 4.5: OMC of Samples



(a)



(b)



(c)

Graph 4.6 (b) Relationship between MDD and OMC for Stabilized Mixes Graph 4.7: (a) FSI Value of Samples, (c) 4.8: UCS Value of Samples (7, 14, 28 Days)

V. CONCLUSION

The research examined the synergistic role of Fly Ash, Hydrated Lime, and Waste Glass Powder in enhancing the geotechnical characteristics of expansive soil (Black Cotton Soil) from the Raipur region. The results indicated that the integration of these three stabilizers greatly improved the engineering properties, volumetric stability, and structural application of expansive soils for sustainable construction purposes.

The following specific conclusions can be drawn from the study:

- Plasticity Reduction:** The Atterberg limits dropped drastically with the increment of the triple-binder content. The Liquid Limit reduced from 65.4% to 42.0%, and the Plasticity Index (PI) fell from 37.6% to 11.0% at the optimum mix (M3). This transition signifies that the soil shifted from a "High Plasticity" (CH) category to a "Low Plasticity" zone, significantly reducing volume change behaviour.
- Swelling Control:** The Free Swell Index (FSI) changed substantially, dropping from 125% to 32%. This indicates that the pozzolanic reactions and the filler effect of Waste Glass Powder successfully restricted the water-absorption capacity of clay minerals.
- Compaction Efficiency:** The Maximum Dry Density (MDD) was raised from 1.61 g/cc to 1.73 g/cc, and the Optimum Moisture Content (OMC) was lowered, demonstrating an improved soil structure. The fine particles of Waste Glass Powder acted as an excellent micro-filler, enhancing the packing efficiency of the soil matrix.
- Strength Enhancement:** Strength parameters showed exponential growth. The CBR (Soaked) value improved from 2.4% to 14.8%, and the UCS (28-day) reached 855 kPa, making the stabilized soil an ideal choice for highway subgrades and light structural foundations in Chhattisgarh.
- Optimum Mix:** It was observed that Mix M3 (15% Fly Ash + 5% Lime + 10% Waste Glass Powder) provided the best balance between density, strength, and durability.

6. Sustainability: The adoption of these waste materials helps in sustaining the environment by recycling urban glass waste and industrial fly ash, thereby reducing the carbon footprint compared to traditional cement stabilization.

5.2 Recommendations for Further Studies

While the study effectively demonstrates the advantages of this triple-binder system, additional research can be performed to expand its technical mechanism:

1. Durability Cycles: Future research should inquire into the long-term performance under wet-dry and freeze-thaw cycles to simulate Raipur's extreme climatic variations.
2. Micro-structural Analysis: Utilizing SEM (Scanning Electron Microscopy) and XRD (X-Ray Diffraction) to observe the formation of C-S-H and C-A-S-H gels would provide a deeper understanding of the chemical bonding between glass powder and lime.
3. Alternative Sources: Research could include varying glass powder particle sizes (nano-glass) and different fly ash sources from various power plants like NTPC Korba or Bhilai Steel Plant.
4. Field Trials: Large-scale field campaigns are important to verify laboratory findings under actual traffic loads and natural weather conditions.
5. Hybrid Reinforcement: The influence of combining this chemical stabilization with Geosynthetics or Jute Fibers can be examined for high-embankment projects.

5.3 Limitations

Despite significant observations, certain limitations should be recognized:

1. Controlled Environment: The experiments were completed in a controlled laboratory, which may not fully reflect field heterogeneity, drainage issues, or groundwater fluctuations.
2. Material Specificity: The research utilized one specific type of Class F Fly Ash and local waste glass. Variations in glass chemistry or fly ash combustion processes might lead to different results.
3. Short-term Focus: The study primarily focused on short-term mechanical properties (up to 28 days). The resistance to repeated dynamic loading or long-term ageing (beyond 1 year) was not investigated.
4. Testing Scope: Advanced tests such as Triaxial Shear Tests or Consolidation Tests were omitted, which are necessary for deep foundation settlement analysis.
5. Environmental Leaching: While glass is inert, a detailed leaching study for heavy metals in fly ash was not performed to confirm 100% environmental safety for groundwater.

5.4 Future Scope

The results suggest a range of opportunities for future applications:

1. Infrastructural Scale: Large-scale application in Naya Raipur Smart City projects, specifically for road embankments and low-cost housing foundations.
2. Hybrid Binders: Exploring the performance of glass powder with other additives like GGBS (Ground Granulated Blast-furnace Slag) or Rice Husk Ash for even higher strength gain.
3. Digital Modelling: Utilizing Geotechnical Modelling (PLAXIS or GeoStudio) to aid the evaluation of stabilized subgrade performance over a 20-year design life.
4. Policy & Standards: Developing specific guidelines and IS-standard protocols for the use of glass-waste based soil stabilization will promote broader industrial application.
5. Circular Economy: This research paves the way for "Green Geotechnics," where urban waste conversion directly contributes to sustainable engineering and waste management goals.

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