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Original Article

Expansive Soil Stabilization using Geopolymer for Subgrade Applications Utilizing a Blend of Rice Husk Ash, Fly Ash, and Ground Granulated Blast Furnace Slag

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Abstract - *This research investigates the utilization of geopolymer technology for stabilizing expansive soils, with a particular emphasis on BC soil. Further study in the area of geopolymerization encompasses an experimental evaluation of geopolymers synthesized from the blend material, which contains fly ash, Rice Husk Ash (RHA) and Ground Granulated Blast Furnace Slag (GGBFS)to enhance the strength and stability of BC soil. Comprehensive testing revealed that geopolymer-stabilized soils demonstrate superior strength and sustainability characteristics, contributing to the advancement of soil engineering practices. The effects of adding additives play a role in changing the behaviour of BC soil, which is demonstrated by a thorough examination of the time-dependent evolution of structural properties. Interestingly, the modified geopolymer composition led to notable improvements in the properties of BC soil, which tends to increase in the strength (UCS) 8.6 MPa, which is remarkable, a decrease in the Atterberg's limits found during the testing which results from the Plasticity Index (PI) of 7.31%, Plastic Limit (PL) of 45.14%, and Liquid Limit (LL) of 50.81%. These findings support the possibility that geopolymer stabilisation could be a game-changing strategy for resolving the issues with BC Soil.*

Keywords - *Geopolymer, Expansive soil, Fly ash, GGBFS, RHA, Stabilization.*

1. Introduction

Soil is a common main material used in civil engineering projects, especially road building. Local soil properties, however, may not always match project specifications. Enhancing the characteristics of the soil provides a workable solution to these issues (Khan et al., 2021). When silt and clay-containing soils are moist during the monsoon season and dry throughout the summer, they often experience problems like decreased strength. For instance, BC soil's swelling properties cause it to weaken significantly under rainy weather conditions (Kumar M. 2020).

BC soil poses unique challenges for civil engineers because of its extreme sensitivity to moisture fluctuations, which result in notable volume changes throughout the year. This soil shrinks significantly during dry seasons, creating deep fissures up to one meter deep and 10–20 cm wide. The soil's fertility is increased by these cracks, which provide deeper oxygen penetration. Approximately 5.46 lakh square kilometers of black cotton soil are found in southern India and central India, mostly in Maharashtra, Madhya Pradesh, and Gujarat (Nikhil T. et al.,2023). which have moderate quantities of lime and magnesium carbonate and are high in alumina and iron oxide, but the soil's potash, nitrogen, and humus content is lacking. The process of stabilizing soil, which may be accomplished chemically or mechanically, increases the soil's ability to support loads and gives it more stability (Makode et al., 2022). Adding ingredients like fly ash, cement, or lime is a common part of this process. These compounds boost resilience to environmental changes, especially moisture fluctuations, and assist in reciprocating the qualities of treated soil via chemical interactions with soil particles. This process is vital for long-term support in projects like road subgrades and foundations, providing an effective strategy to tackle issues associated with fluctuating environmental conditions (Makode et al., 2022).

To evaluate the potential of geopolymer-based soil stabilization in improving soil strength and sustainability by optimizing mix proportions. The study aims to establish correlations between mix design parameters and stabilization performance, providing a sustainable alternative to traditional soil stabilization techniques. The results show that the geopolymer mixture exhibits a potential to contribute to environmentally friendly and durable solutions for soil stabilization, showcasing its viability as a valuable technique in geotechnical engineering practices. In this paper, the evaluation shows the major effects of blending fly ash-GGBFS-RHA as a geopolymer precursor, which results in higher UCS as a strength parameter (Tan, E. H. et al.2020).

1.1. Geopolymer Soil Stabilization

Research suggests that geopolymerization depends on silica and aluminum are necessary for constructing polymeric frameworks in an alkaline environment; research indicates that geopolymerization relies on raw materials high in these elements, particularly in amorphous forms. Additionally, in the process, calcium is needed to act as a cementing material during the hydration for the formation of stable compounds to increase the strength and reduce the plasticity index, compounds like calcium silicate hydrate, aluminosilicate hydrate, and calcium aluminosilicate hydrate (Singh et al., 2021; Abdila et al., 2021). These compounds are very crucial in the process of gaining strength in the geopolymerzation process. In the same process, an aluminosilicate powder combines with an alkaline solution to form a fast-hardening paste that solidifies into a durable geopolymer. This rapid setting process restricts the formation of a highly crystalline structure, giving geopolymers a dense, polycrystalline form, unlike the cage-like crystalline structure found in zeolites. This structural difference enhances the mechanical properties of geopolymers, enhancing their resilience and strength (Abdullah et al., 2021).

The specific ratios of oxides, such as Ca, Si, and Na, directly influence the microstructure and mechanical characteristics of the resulting geopolymer products. Adjusting these ratios allows for control over the technical attributes and strength of the geopolymer. These high-calcium alkaline-activated compounds are formed from a combination of CaO, SiO_2, Al_2O_3, and H_2O. Stabilizing soil by chemical or mechanical means offers an environmentally friendly way to increase the soil's stability and load-bearing capability. In order to help the reciprocated geotechnical qualities of the treated BC soil, this method usually includes additives like fly ash, cement, or lime, which interact chemically with the soil particles (Nguyen et al., 2020).

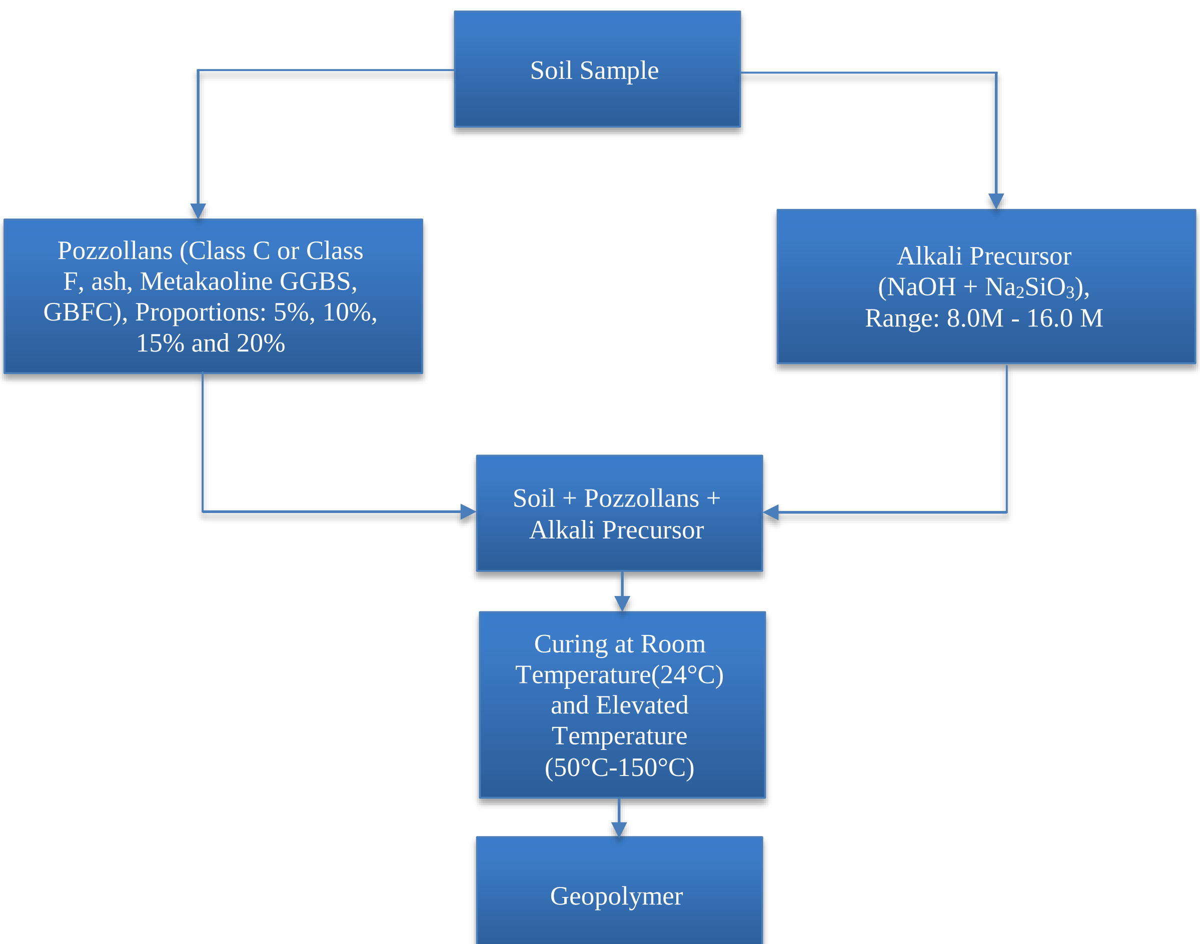

Fig. 1 Standard geopolymer composition and design [5]

A specific Ca/Si ratio between 0.85 and 1.8 is necessary to develop stable gels. Similarly, it is found that the sodium to silicate ratio is on the higher side by its ratio value of 0.25, which is important required for the formation of sodium calcium silicate hydrate and sodium calcium aluminosilicate hydrate as gels. The above-mentioned gels are essential in determining geopolymer materials' required strength and mechanical characteristics. Despite their encouraging prospects, geopolymer technology's broad use (Yaswanth et al.,2022). The sluggish commercialization process of geopolymers can be attributed to uncertainties surrounding their chemical composition and variability in their properties. These materials' mechanical and thermal characteristics can differ, raising questions about their readiness for industrial and commercial use. Experimental inconsistencies often stem from improper sample preparation or inaccurate control of system variables, as observed in the study (Parthiban et al., 2022).

The ratio of silicon to aluminum (Si/Al) significantly impacts the molecular structure of geopolymers, affecting both their chemical and physical characteristics. This geopolymer creates a strong, three-dimensional lattice that is usually brittle and rigid when the Si/Al ratio is less than 3. Because of their similar structural rigidity and durability, these characteristics make these geopolymers suitable for applications where conventional cements and ceramics are used. The bond of the geopolymer becomes more elastic and two-dimensional when the Si/Al ratio is more than three (Christopher et al., 2021; Saxena et al., 2022). This modified structure imparts less stiff and more flexible properties, similar to rubber-like substances or other sticky materials.

In contrast to the stiffness of cement or ceramic-like materials, these characteristics make these kinds of geopolymers perfect for applications where some flexibility or elasticity is advantageous. This adaptability in geopolymers' physical characteristics, which are determined by the Si/Al ratio, emphasizes their potential for a wide range of uses, from more flexible, adhesive-type goods to stiff building materials (Atan, E. et al., 2021). A combination of fly ash, crushed, granulated blast furnace slag, and rice husk ash is used to stabilize expansive soil using geopolymer for subgrade applications.

2. Theoretical Framework

Because geopolymer stabilization has the potential to be an environmentally benign alternative to traditional stabilizing methods that also lessen carbon emissions, it has garnered a lot of attention. The aluminosilicate precursor material is used in geopolymerization to activate the alkaline solutions, creating a robust and long-lasting matrix (Kheimi et al., 2022). By lowering the heavy reliance on cement addition, which contributes significantly to pollution through the release of extremely hazardous gases like CO_2, geopolymerization aids the environment. (Atan and others, 2021). demonstrated how well high-concentration sodium hydroxide (NaOH) solutions (≥10M) may be used to measurably increase stabilized soils' compressive strength. However, because concentrated alkaline solutions are expensive and hazardous, they pointed out handling and economic feasibility issues. The use of industrial wastes and byproducts, like fly ash and slag, as precursors for geopolymers has been investigated by numerous researchers (Capasso et al., 2021). Fly ash is used to create a basis for geopolymers, improving soil characteristics, including Unconfined Compressive Strength (UCS), and boosting durability for civil engineering subgrade applications. However, these studies frequently ignore the difficulties in using geopolymer technology in expansive soils, like black cotton soil, which present particular difficulties because they tend to inflate and shrink. There is still little research on using geopolymer compounds to stabilize black cotton soil. Although they have shown success in reducing swelling, traditional techniques, such as using cement or lime, are not environmentally friendly (Syed M. et al., 2022). Recent studies assess the performance of geopolymers in a range of circumstances and applications in order to optimize the mix design process. The economic and safety implications of utilizing lower-concentration NaOH solutions, for example, were not covered in the investigations of Nabizadeh Mashizi et al. (2023), despite the fact that they stressed the significance of mix optimization in reaching desired mechanical qualities. The use of high-concentration solutions (such as 12M NaOH) for geopolymerization has not been thoroughly investigated, even though much of the literature stresses low molarity activators. This disparity emphasizes the necessity of researching to strike a balance between cost, safety, and strength performance, especially for expansive soils like black cotton soil.

The studies on soil stabilization highlight key gaps that need to be addressed to advance the field. One major gap is the lack of studies on long-term durability and environmental sustainability, as most focus primarily on short-term strength improvements. Evaluating the resilience of stabilized soils to environmental factors and assessing their ecological impact is essential for developing sustainable solutions (Hamed et al.,2022). The potential of cost-effective and locally sourced materials, such as agricultural residues or natural fibers, remains underexplored, despite their promise for affordable and eco-friendly stabilization. Comparative studies under standardized conditions are also necessary to determine the most effective stabilization techniques for specific soil types in geotechnical engineering to gain the optimum performance on the strength and durability parameters while considering its approach to a sustainable environment. To address the problem definition and gap analysis, this study contributes to developing a viable model in the field of soil stabilization to obtain the goals in economics and a sustainable model for efficient development (Giroudon et al., 2021).

3. Materials and Methods

For the investigation and research for the blending to form a geopolymer mixture, fly ash, Rice Husk Ash (RHA), and Ground Granulated Blast Furnace Slag (GGBFS) are used with the help of alkaline activator, which consists of chemicals like NaOH and Na2SiO3, to increase the strength and resistance of BC soil. This promotes geopolymerization to get BC soil's desired strength by blending the above material and activator.

3.1. BC Soil

In the research in geopolymerization for gaining high strength in BC soil, the sample of soil was taken from Nagpur, India, which was distinguished by its fine-grained, extremely malleable characteristics as well as its noticeable swelling and shrinking patterns. According to UCS criteria and the AASHTO system, the expansive BC soil is categorized as high-plasticity clay (CH) by its properties, as shown in Table 2, which was confirmed by determining its index properties in compliance with IS 2710 Part V (1985). The soil's particle size and properties are shown in the table, as shown in Figure 2, which was determined by the XRF method to find BC soil's chemical properties and composition. Important main elements were determined iron oxide (FeO_3), silicon dioxide (SiO_2), and aluminum oxide (AlO_3). Table 1 presents the precise chemical composition results.

Silicon dioxide (SiO_2), aluminum oxide(Al_2O_3); iron oxide(Fe_2O_3); calcium oxide (CaO); magnesium oxide (MgO); potassium oxide (K_2O); titanium oxide (TiO_2); sodium oxide (Na_2O); Loss of Ignition (LOI)

Table 1. Chemical composition of BC soil

SiO_2	Al_2O_3	Fe_2O_3	Cao	MgO	K_2O	TiO_2	Na_2O	LOI
55.29	13.56	11.14	3.66	2.38	0.99	1.97	0.38	10.04

Table 2. Black cotton soil properties

Serial No.	Type of Tests	Units	Index Values
1	Specific Gravity	-	2.75
2	Free Swell Index (FSI)	%	70
3	Plastic Limit (PL)	%	35.9
4	Liquid Limit (LL)	%	88.4
5	Plasticity Index (PI)	%	52.5
6	Optimum Moisture Content (OMC)	%	26
7	Maximum Dry Density (MDD)	kN/m^3	12.8
8	Soil Classification, USCS	-	CH

Table 3. Chemical composition of fly ash by XRF

$SiO_2+Al_2O_3+Fe_2O_3$	SiO_2	MgO	SO_3	Total Chloride	LOI
79.1	38.4	2.53	0.651	0.0044	1.7

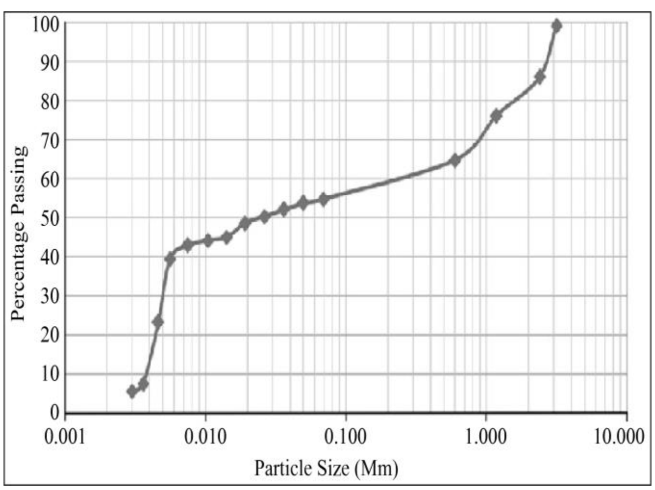

Fig. 2 Grain size analysis of BC soil

3.2. Fly Ash

To investigate, we took a sample of Fly ash from the Koradi Thermal Power Plant for further investigation. This fly ash is categorized as Class (F) fly ash because of its lower calcium concentration.

ASTM C618 (2010) states that the classification, due to its characteristics it contains main constituents AlO_3 (13.56%), SiO_2 (38.4%), and FeO_3 (11.14%) exceeds 70%. The further findings after the XRF test are shown in Table 3, confirming that AlO_3, SiO_2, and FeO_3 are the main phases.

Further information about the FA's particle size properties may also be found in Figure 3, which shows the investigated particle size analysis.

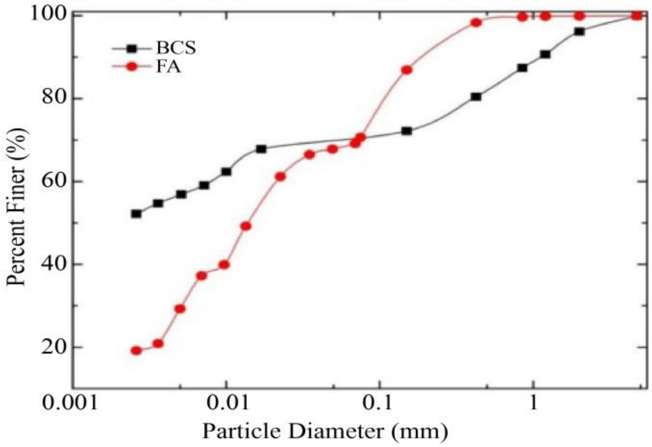

Fig. 3 Analysis of grain size-black cotton soil and fly ash

3.3. Ground Granulated Blast Furnace Ash

The above results of the BC soil chemical composition Table 5 shows the specific findings about the GGBFS. Iron oxide (Fe_2O_3), silicon dioxide (SiO_2), and aluminum oxide (AlO_3) are the main elements found in the soil.

Fine-grained BC soil is highly plastic soil that shows notable swelling and shrinkage characteristics, and it falls under the AASHTO and UCS classifications for clay with high plasticity (CH).

Table 4 summarizes the index parameters of the soil, which were established using the IS 2710 Part V (1985) standard. These index characteristics, which show high flexibility, further support the soil's designation as CH.

Table 4. Physical properties of GGBFS

Physical Property	Particle Size	Specific Gravity	Color	Bulk Density (kg/m³)	Fineness (m²/kg)	Moisture Content
Approximate Value	Micrometers to tens of micrometers	2.8 - 3.0	Light gray	900 - 1200	350 - 600	Less than 1%

Table 5. Chemical composition of GGBFS [10, 11]

Chemical Composition	Silica (SiO_2)	Alumina (Al_2O_3)	Calcium oxide (CaO)	Iron oxide (Fe_2O_3)	Magnesium oxide (MgO)	Sulfur trioxide (SO_3)	Trace elements
Typical Range	35% - 45%	15% - 30%	30% - 40%	0.5% - 5%	Minor component	Minor component	Varies

Table 6. Physical properties of RHA

Physical Property	Particle Size	Specific Gravity	Color	Bulk Density (kg/m³)	Porosity	Surface Area	Silica Content (SiO_2)	pH
Approximate Value	Fine particles, a range of micrometres	2.0-2.2	Grayish-white to light tan	600-800 kg/m³	High	15,000-25,000m²/kg	>90%	9-11

Table 7. Chemical composition of RHA

Chemical Composition	Silica (SiO_2)	Alumina (Al_2O_3)	Calcium oxide(CaO)	Iron oxide (Fe_2O_3)	Magnesium oxide- (MgO)	Potassium Oxide (K_2O)	Loss in Ignition
Typical Range	93.4 %	o.57 %	0.53 %	0.24 %	0.39 %	2.95	1.17

3.4. Rice Husk Ash

The RHA material is the agricultural waste generated from the rice milling process; the waste material is called husk, which we used as an RHA and was sourced from the Gondia district for this study. RHA's primary component is silica (SiO_2), which constitutes over 90% of its composition and exists in an amorphous form, giving RHA unique adaptability for diverse applications. Besides silica, RHA contains small amounts of carbon, with its concentration influenced by combustion and other conditions. This carbon content further contributes to the specific properties of RHA. Additionally, RHA contains trace amounts of many metals in different proportions, including potassium, calcium, magnesium, aluminum, iron, and sodium. Tables 6 and 7 display the specific chemical makeup and RHA characteristics examined in this investigation.

3.5 Alkaline Liquid

In this study, a 12M NaOH solution was selected to prepare specimens, providing the necessary alkalinity for the geopolymerization process. This high-molarity solution helps activate the source materials, allowing them to bond effectively and form a stable geopolymer structure. 3. The molecular weight of NaOH is used to create the 12M NaOH solution, which is 40.00 gm/mol and is multiplied by 12 to reach the target molarity. This calculation results in 480 grams of NaOH required to achieve the 12M concentration when dissolved in one liter of water. Preparing the alkaline liquid involves at least one day before use and mixing sodium hydroxide and sodium silicate solutions before use. This advanced preparation ensures thorough blending and consistency, allowing the alkaline solution to perform optimally during specimen formation. Therefore, 1000 grams of water is combined with 480 grams of NaOH to prepare the solution, producing 1480 grams of alkaline liquid. This specific preparation method yields a consistent and effective NaOH solution for the study.

3.6. Geopolymerization

The mixture is moulded for sample preparation in the specified desired shape, and the sample is cured at room temperature. During its curing period, a chemical reaction occurred, resulting in a durable binding agent. The alkaline solution activator is prepared by using the sodium hydroxide (NaOH) solution to provide the necessary alkalinity that initiates the geopolymerization reaction. This alkaline solution is thoroughly mixed with the selected source materials to ensure uniform distribution. The process begins with selecting initiated materials that are highly rich in silica content (SiO_2) with the content of alumina powder (Al_2O_3), with blending, blending Fly ash with GGBS and RHA. The above material was used for the formation of a geopolymer mix.

3.7. Blending, Sample Preparation, and Sample Testing

As per the study of the American Coal Ash Association (2003), the standard practice for soil stabilization typically involves incorporating 10–30% Class-F Fly Ash (FA). This research of BC soil with different proportions of blending materials in the parts of 10%, 15%, 20%, and 30% to explore their effectiveness in geopolymer BC soil stabilization. The NaOH solution used for the treated samples had a 12M concentration, prepared by pellets of NaOH dissolved in distilled water. The concentration is used to optimize the cost and safety, providing the necessary alkalinity for the geopolymerization process. The impacts of blending FA, GGBFS, and RHA on the soil's OMC, MDD and its consistency limits and UCS were assessed following IS 2720 Part VII (1980) and Part V (1985) standards. In the standard sampling process, cylindrical block (50d and 100 h) specimens were prepared with these specifications, with the quantities of BCS, FA, GGBFS, and RHA based on the previously determined MDD. Two sets of specimens were prepared: one set untreated with any stabilizers, mixed with water, and another treated set using an alkaline NaOH solution. The sample sets were tested at room temperature. In further examination, the moisture content of the BC soil block was determined at its optimum moisture content Maximum Dry Density (MDD). The samples were compacted as per IS standards, and the available samples were wrapped in plastic material and then cured in an observation at room temperature; further testings were carried out to determine the UCS after an interval of 7, 14, and 28 days, all the process are carried according to IS 4332 Part V (1970). The three specimen samples were taken from each curing period and tested to ensure the results.

4. Results and Discussions

4.1. Blending Effects of the Materials on Atterberg's Limits

When fly ash, GGBFS, and RHA concentrations are higher, BCS's Plastic Limit (PL) rises. This is because the larger, coarser fly ash particles promote flocculation, and the blend materials' double-layer particles become thinner (Sivapullaiah & Sridharan, 1985). The soil becomes less plastic due to the stabilizers' contact, which modifies the consistency limitations. The addition of blend materials impacts the BC soil's atterberg limits (LL, PL, and PI), as seen in Figures 4, 5, and 6. When these additives are added, the relation of LL, which is linked to the dispersed thickness of the multi/double layer that is encircled by clay particles at its surface (Sivapullaiah, Prashanth, & Sridharan, 1996), essentially stays the same. A decrease in the Plasticity Index (PI) is noted when the amount of additives in the BCS mixture rises. This decrease suggests that the plastic behavior of the soil is reduced, making it less expansive and more stable, which can increase its suitability for engineering uses. Clay particles agglomerate when these stabilizers are added, changing the BCS's overall structure. As the amount of fly ash, GGBFS, and RHA content increases, the cohesiveness of the soil decreases due to this change in particle arrangement, reflecting an increase in PL.

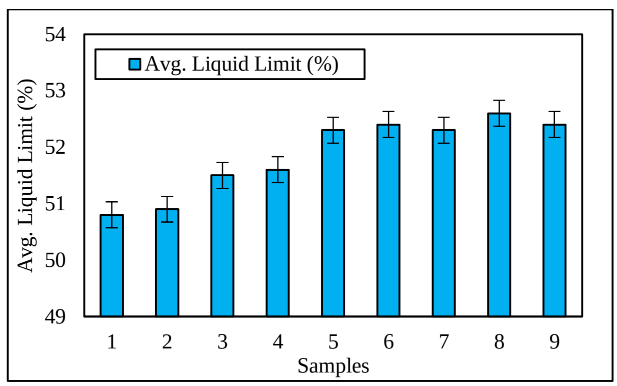

Fig. 4 Average liquid limit

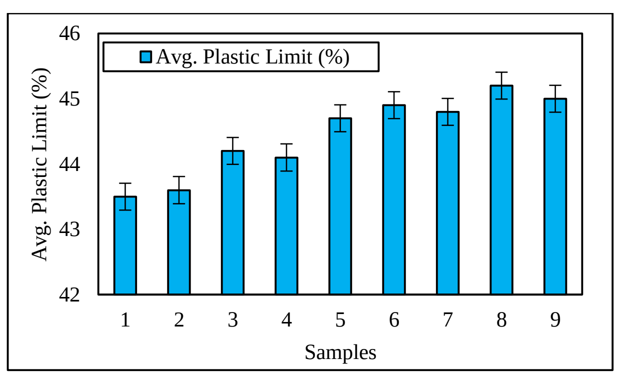

Fig. 5 Average plastic limit

4.2. Comparative Analysis

The impact of RHA as a stabilizing material on the UCS of soil is evaluated by a comparative analysis with and without RHA. UCS values were recorded throughout three curing periods of seven, fourteen, and twenty-eight days to analyze the strength progression over time.

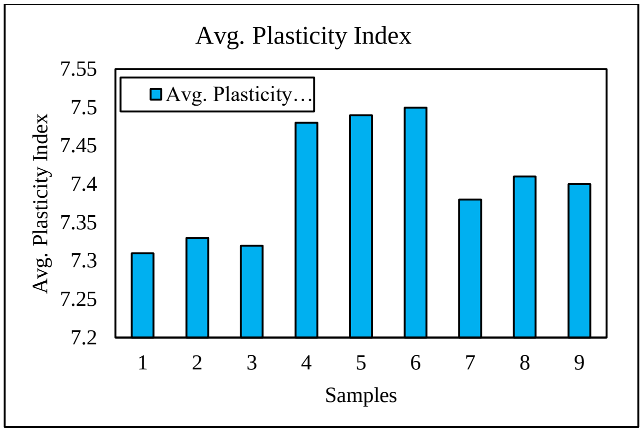

Fig. 6 Average plasticity index

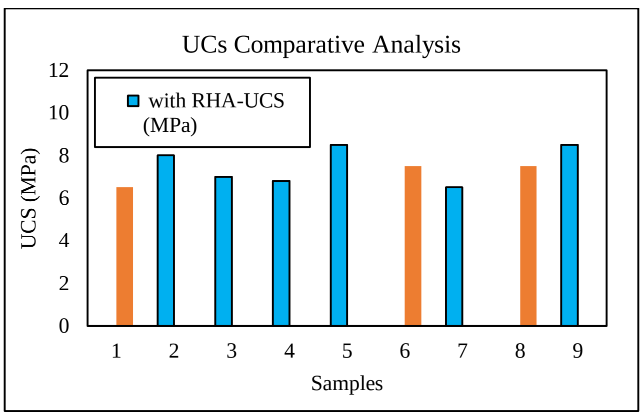

Fig. 7 Comparative analysis of USC with and without RHA

The peak UCS of 8.7 MPa was reported by sample S5 out of all the RHA-incorporated samples, suggesting that the right amount of RHA can significantly increase soil strength. Compared to the mix without RHA addition, the graphical representation indicates that the UCS value rises with the addition of RHA. Based on the evaluated samples, the RHA has been found to improve the UCS of stabilized Black cotton soil. In addition, samples S1, S6, and S8 have the lowest UCS values of all the samples, ranging from 6.50 MPa to 7.40 MPa, demonstrating the benefits of RHA inclusion.

4.3. Comparative Analysis of Average UCS

The graph illustrates that the highest UCS value is achieved by Sample S5, emphasizing the effectiveness of this specific mix in enhancing soil strength. The analysis focuses on UCS values, revealing that Sample S5, which includes Fly Ash (FA), GGBS 20 % respectively and a part of RHA 30 %, exhibits the highest average UCS. The comparative analysis examines the effects of blending RHA as a strength-improving agent in BC soil. It helps to determine the UCS of a material with the help of activation agents and additives.

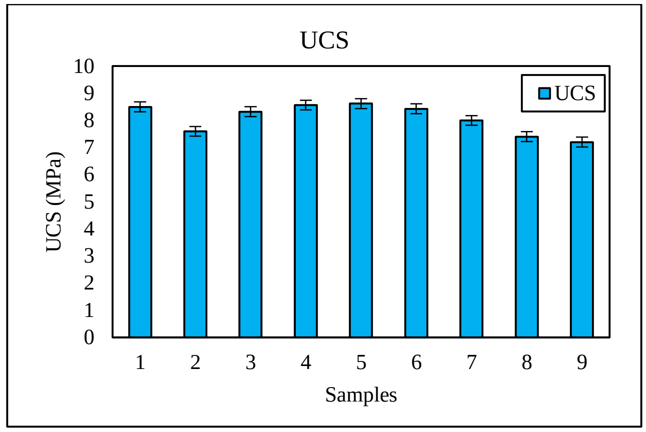

Fig. 8 Optimal UCS performance of sample S5 with FA-20%, GGBFS-20%, and RHA-30%

5. Conclusion

The experimental investigation conducted aimed to evaluate and determine the viability of blending fly ash, GGBFS and RHA as a geopolymer for stabilizing swelling soils.

The conclusions derived from the experimental study and their analytical results:

- Applying geopolymers at room temperature by blending the fly ash, GGBFS, and RHA significantly enhanced and improved BC soil's properties, demonstrating the potential of blending material with an alkaline activator for effective improvement by using these stabilizing agents.
- Unconfined Compressive Strength (UCS) tests revealed a considerable increase in strength in geopolymer-treated Black Cotton Soil over varying curing periods. The peak UCS value of 8.620 MPa confirms the substantial enhancement of soil strength characteristics due to geopolymer stabilization.
- The Plasticity Index (PI) was determined to be 7.31%, with Liquid Limit (LL) and Plastic Limit (PL) values of 50.81% and 45.14%, respectively, providing crucial insights into the soil plasticity and moisture retention behavior. These findings underscore the improved stabilization properties of geopolymer-treated BC soil.

The study underscores the promising potential of geopolymer derived from fly ash, GGBFS, and RHA for soil stabilization, significantly improving strength and plasticity. This approach presents a practical solution to the challenges associated with expansive soils.

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