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FIBER REINFORCED GEOPOLYMER SOIL STABILIZATION

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Abstract: This research explores the effectiveness of geopolymer-based soil stabilization enhanced by natural coir fiber reinforcement, using Ground Granulated Blast Furnace Slag (GGBFS) as the main aluminosilicate precursor and sodium hydroxide as the alkaline activator. A methodical experimental strategy was implemented, starting with the adjustment of GGBFS content (5–25%) to identify its optimal level, followed by the optimization of sodium hydroxide concentration (2M–14M), and ultimately, the integration of coir fiber in different percentages (0.5–2%). The ideal mixture—20% GGBFS, 10M NaOH, and 1% coir fiber—was subjected to Unconfined Compressive Strength (UCC), California Bearing Ratio (CBR), and Atterberg limit assessments. The results indicated notable enhancements in compressive strength and load-bearing capacity, with the peak UCC reaching 112.77 kN/m². Curing effects were also examined under various conditions, showing improved strength with prolonged curing time. The inclusion of coir fibers enhanced ductility and crack resistance, while the utilization of industrial by-products and natural fibers promotes environmental sustainability. The results affirm that fiber-reinforced geopolymer stabilization presents a feasible, eco-friendly alternative to traditional soil enhancement methods.

Keywords: Geopolymer soil stabilization, ground granulated blast furnace slag, coir fiber reinforcement, sodium hydroxide activator, unconfined compressive strength, California bearing ratio, Atterberg limits, sustainable construction, eco-friendly stabilizers, alkali-activated binders.

I. INTRODUCTION

Soil is extensively utilized as a construction material worldwide for a variety of applications; however, some soils possess inherently poor properties that require engineering prior to use. Soil stabilization is a technique used to enhance the physical and engineering characteristics of soil, thereby improving its strength, durability, and overall performance for construction and other uses. This method is especially vital in civil engineering, as the stability of soil has a direct impact on the integrity of structures such as roads, foundations, and embankments.

There are numerous soil stabilization methods, which can be generally classified into mechanical, chemical, and physical techniques. Mechanical stabilization entails the physical alteration of soil particles, often through compaction or the incorporation of aggregates to boost the soil's density and load-bearing capacity. Conversely, chemical stabilization involves the use of various additives, such as lime, cement, or fly ash, which interact with the soil to create bonds that enhance strength and decrease plasticity. Physical stabilization encompasses techniques like geosynthetics or soil reinforcement that improve the structural integrity of the soil without changing its chemical makeup.

The selection of a stabilization method typically hinges on the specific properties of the soil in question, including its type, moisture content, and the intended application of the stabilized material. For instance, clayey soils, which are susceptible to swelling and shrinkage, may greatly benefit from chemical stabilization using lime or cement. In contrast, sandy soils, which can be loose and weak, can be effectively enhanced through mechanical methods or the addition of geosynthetic materials. By optimizing soil properties, stabilization not only improves the performance of construction projects but also prolongs their lifespan and minimizes maintenance expenses.

Geopolymer soil stabilization is a cutting-edge method that improves the engineering characteristics of soil through geopolymer technology. This technique entails treating soil with geopolymeric binders, which are activated aluminosilicate substances that enhance the soil's strength, durability, and overall functionality. The main objective of this strategy is to boost the load-bearing capacity of weak or unstable soils, rendering them appropriate for construction and infrastructure projects.

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The stabilization process starts with choosing suitable aluminosilicate materials, like fly ash or metakaolin, which are mixed with an alkaline activator. When combined with the soil, the geopolymer binder experiences a chemical reaction, leading to a solidified matrix that binds soil particles together. This reaction not only boosts cohesion among soil grains but also improves the soil's resistance to environmental factors such as moisture, temperature variations, and chemical degradation.

One of the primary benefits of geopolymer soil stabilization is its sustainability. In contrast to traditional stabilization methods, that frequently depend on cement or lime, which can lead to considerable carbon emissions, geopolymer technology makes use of industrial byproducts, thereby encouraging recycling and minimizing the overall environmental impact. Moreover, the application of geopolymer binders often results in enhanced durability, allowing treated soils to retain their strength and stability over extended periods, even in challenging conditions. Additionally, geopolymer soil stabilization can be customized to fulfill specific project needs. The characteristics of the geopolymer mixture can be modified according to the soil type, required strength, and environmental circumstances. This versatility renders it appropriate for a range of applications, including road construction, earthworks, and foundation stabilization. As research continues to progress, the implementation of geopolymer technology in soil stabilization is anticipated to increase, offering a sustainable alternative to traditional methods and aiding in the advancement of eco-friendly construction practices.

II. LITERATURE REVIEW

Syafiadi Rizki Abdila. et al. (2022) aims to review the use of fly ash and ground granulated blast furnace slag (GGBFS)-based geopolymers for soil stabilization by improving strength. Previous studies utilized only one type of precursor: either fly ash or GGBFS, but the resulting strength values did not satisfy the ASTM D 4609 (<0.8 Mpa) standard necessary for soil-stabilizing criteria in road construction applications. This research focuses on the combination of both types of precursors, namely fly ash and GGBFS. The results of an unconfined compressive strength (UCS) test on the stabilized soil samples are discussed. In conclusion, the paper asserts that GGBFS and fly ash-based geopolymers can effectively serve as binders for soil stabilization techniques. However, further research is needed to comply with the ASTM D 4609 standard for road construction applications, especially in subgrade layers.

Mukhtar Hamid Abeda et al. (2024) develops eco-friendly mechanochemically activated geopolymers (MAG) for soil stabilization and compares them with conventional geopolymers (CAG). The study assesses the effects of GGBS content and sulfate exposure on strength and durability. MAG demonstrated a 12–45% increase in UCS compared to CAG prior to exposure. Strength improved by 114%, 247%, and 361% with 50%, 75%, and 100% GGBS, respectively. After being immersed in 1% $MgSO_4$, MAG exhibited superior durability, maintaining 93% UCS at 60 days and 70% at 120 days, in contrast to CAG's 89% and 58%.

S.C. Boobalan et al. (2022) examines the stabilization of expansive soil through the use of lime and coir fibers, which are recognized for their high lignin content and tensile strength in moist conditions. Soil samples from Kuniamuthur, Coimbatore were analyzed for their index properties and strength characteristics. Experiments were carried out with coir fiber content ranging from 0 to 1.5% and 5% lime, focusing on CBR, UCS, and shear strength assessments. The findings indicated that CBR improved with fiber content exceeding 1.5%, while UCS and shear strength reached their maximum at 1% fiber and 5% lime. Therefore, the combination of 1% coir fiber and 5% lime is deemed optimal for effective soil stabilization.

Ehsan Kasehchi et al. (2024) explores the geopolymer stabilization of silty sand soil utilizing ceramic waste powder (CWP) and sodium hydroxide (NaOH) as an alkali activator. The objective was to enhance the mechanical properties of inshore sand sustainably. XRF analysis was conducted to determine the chemical composition of CWP and the soil. The study evaluated the impact of CWP content (ranging from 0 to 24%), NaOH concentration (0 to 15 M), curing duration (7, 28, and 91 days), and initial curing temperatures (25°C and 70°C) on UCS and failure strain ($\mathcal{E}f$). The optimal mixture (15% CWP, 6 M NaOH, cured for 28 days) resulted in an increase in UCS from 0.080 to 2.22 MPa and $\mathcal{E}f$ from 2.31% to 5.45%, surpassing the performance of soil stabilized with 5% OPC. In the absence of NaOH, CWP did not enhance strength. However, 2 M NaOH alone increased UCS to 0.36 MPa after 7 days. Elevated curing temperatures (70°C) enhanced UCS by as much as 2.04 times. SEM and EDX analyses validated significant microstructural development and the formation of aluminosilicate gel.

III. OBJECTIVES / AIMS

- TO OPTIMIZE THE PROPORTION OF COIR FIBERS AND GGBFS TO ACHIEVE THE BEST RESULTS
- TO STUDY THE STRENGTH CHARACTERISTICS OF FIBER REINFORCED GEOPOLYMER STABILIZED SOIL

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- TO OPTIMIZE THE EFFECT OF CURING PERIOD ON THE STRENGTH CHARACTERISTICS OF TREATED SOIL
- TO ACHIEVE SUSTAINABILITY AND LOW ENVIRONMENTAL IMPACT

IV. METHODOLOGY

Literature review
Collection of raw materials
Preliminary tests on soil sample
Collection of additives
Mixing of raw materials
Testing of specimen (UCC, CBR, Atterberg Limits)
Optimum proportions obtained
Curing of optimum samples
Testing of the samples (UCC)
Result and discussion

V. MATERIALS USED

Soil

Clayey soils are well-known for their problematic characteristics in civil engineering applications. Their high plasticity, low strength, and sensitivity to moisture fluctuations render them unsuitable for direct application in infrastructure without modification. These soils experience considerable volume changes—expanding when wet and contracting when dry—resulting in instability, surface cracking, and structural damage. Such challenges are particularly critical in foundations, pavements, and subgrade layers where consistent strength and stability are essential. Consequently, stabilizing clayey soil is vital to enhance its load-bearing capacity, minimize moisture-related deformations, and improve its long-term durability in construction.

In this study, a clayey soil sample was chosen due to its engineering significance and challenging properties. The sample was extracted from a depth of 2 meters below ground level at Punnathara, Kottayam. To maintain its natural state, the soil was promptly sealed in polythene bags to avoid moisture loss. It was subsequently oven-dried for 24 hours and sieved according to the specifications for various laboratory tests.

TABLE 1 PHYSICAL AND MECHANICAL PROPERTIES OF UNTREATED SOIL

Soil Parameters	Values
Moisture Content	45.45%
Specific Gravity	2.73
% clay content	66%
Plastic Limit	25%
Liquid Limit	50%
Shrinkage Limit	23%
Plasticity Index	25%
Maximum Dry Density	16.39kN/m^3
Optimum Moisture Content	24%
CBR Value	1.4%
Unconfined Compressive Strength	22.55kPa

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The initial laboratory assessments revealed the inadequate engineering characteristics of the untreated soil, emphasizing the necessity for stabilization. The soil's water content was recorded at 45.45%, indicating an excessive retention of moisture that could jeopardize structural integrity. The clay content was determined to be 66%, which signifies a high level of plasticity and a propensity for considerable shrink-swell behavior. The plastic limit was assessed at 25%, while the liquid limit was noted at 50%, leading to a plasticity index of 25%, categorizing the soil as highly plastic and problematic with moisture fluctuations. The shrinkage limit of 23% indicates that the soil is susceptible to significant volume reduction during drying, potentially resulting in cracking and instability. The compaction properties revealed a maximum dry density of 1.67 g/cc and an optimum moisture content of 24%, values that are within the anticipated range but still highlight the need for strength enhancement. Notably, the California Bearing Ratio (CBR) was merely 1.4%, reflecting a very low load-bearing capacity. The unconfined compressive strength was recorded at only 22.55 kN/m², significantly below the acceptable threshold for structural applications.

These findings clearly illustrate the unsuitability of the natural clayey soil for engineering purposes without stabilization. Consequently, this study seeks to enhance its properties through geopolymer stabilization utilizing ground granulated blast furnace slag (GGBFS), sodium hydroxide, and coir fiber, providing a sustainable and effective approach to improve soil performance.

GGBFS

Ground Granulated Blast Furnace Slag (GGBFS) is a byproduct generated during the steel production process. It is recognized for its pozzolanic characteristics, enabling it to react with alkaline solutions to create a robust binder within the geopolymer matrix. GGBFS offers numerous benefits. It improves compressive strength, enhances durability, and increases resistance to chemical attacks in stabilized soil. Furthermore, its fine particle size aids in better workability and decreases the permeability of the soil mixture.

The incorporation of GGBFS not only fosters sustainable construction practices by recycling industrial waste but also helps in lowering carbon emissions linked to conventional cement manufacturing. GGBFS is sourced from RDC Concrete, Nattakom.

Coir fibers

Coir fiber, a natural and renewable resource derived from coconut husks, is gaining traction for its application in fiber-reinforced geopolymer soil stabilization due to its sustainable, strong, and eco-friendly characteristics. Geopolymers, which are inorganic polymers activated by alkaline solutions, present a viable alternative to conventional cement-based stabilizers. When integrated with coir fiber, they can greatly improve the mechanical properties of soil, such as strength and durability. The natural resistance of coir fiber to microbial degradation, its biodegradability, and its relatively low cost render it an excellent reinforcement material for soil stabilization. This report examines the potential of coir fiber in enhancing soil performance through geopolymer-based stabilization methods, emphasizing its capacity to minimize shrinkage, boost strength, and improve soil structure while ensuring environmental sustainability.

Sodium Hydroxide (NaOH) pellets

Sodium hydroxide (NaOH) is a potent alkali that is essential for activating geopolymer materials. It improves the dissolution of aluminosilicate minerals, aiding in the creation of a reactive gel that is vital to the geopolymerization process.

The strong reactivity of NaOH speeds up the setting time and enhances the early strength of the geopolymer matrix. Its use is justified by its ability to establish a highly alkaline environment, which is crucial for activating materials such as Ground Granulated Blast Furnace Slag (GGBFS). Furthermore, NaOH is relatively low-cost and easily accessible, making it a suitable option for large-scale applications.

VI. MIX PROPORTIONING

The mix design phase focuses on identifying the ideal ratios of geopolymer binder, fiber, and soil. This process necessitates a careful balance among workability, strength, and durability. Generally, an initial trial mix is created, followed by a series of tests to assess the performance of various formulations. Key factors, including the type and length of fiber and the ratio of geopolymer binder, need to be optimized to improve the soil's compressive and tensile strength. Additionally, the incorporation of fibers enhances ductility and crack resistance.

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The mix proportioning in this research was structured in three systematic steps to analyze the impact of ground granulated blast furnace slag, sodium hydroxide concentration, and coir fiber on soil stabilization. Each step involved altering one parameter while maintaining the others constant to identify the best mix for strength enhancement.

TABLE 2 MIX PROPORTIONS OF SOIL, GGBFS, NAOH, COIR FIBER

Mix ID	Untreated Soil (%)	GGBFS (%)	NaOH (M)	Coir Fiber (%)	Curing	Remarks
M0	100	-	-	-	-	-
Phase 1- GGBFS Concentration Variation						
M1	95	5	2	-	-	GGBFS percentage giving maximum UCS Value is noted & it is taken as OG
M2	90	10	2	-	-	
M3	85	15	2	-	-	
M4	80	20	2	-	-	
M5	75	25	2	-	-	
Phase 2- NaOH Concentration Variation						
M6	S - OG	OG	2	-	-	NaOH Molarity giving maximum UCS Value is noted & it is taken as ON
M7	S - OG	OG	4	-	-	
M8	S - OG	OG	6	-	-	
M9	S - OG	OG	8	-	-	
M10	S - OG	OG	10	-	-	
M11	S - OG	OG	12	-	-	
M12	S - OG	OG	14	-	-	
Phase 3- Coir Fiber Concentration Variation						
M13	S – OG	OG	ON	0.5	-	Coir Fiber percentage giving maximum UCS Value is noted & it is taken as OC
M14	S – OG	OG	ON	1	-	
M15	S – OG	OG	ON	1.5	-	
M16	S - OG	OG	ON	2	-	
S + OG + ON + OC = OPTIMUM MIX (OM) Obtained						
OM	S – OG	OG	ON	OC	24hrs oven drying	-
OM	S – OG	OG	ON	OC	7days at ambient temperature	
OM	S – OG	OG	ON	OC	14days at ambient temperature	
OM	S - OG	OG	ON	OC	28days at ambient temperature	

S – Soil Concentration, OG – Optimum GGBFS Concentration, ON – Optimum NaOH Concentration, OC – Optimum Coir Fiber Concentration

In the initial phase, the proportion of ground granulated blast furnace slag was adjusted while keeping the sodium hydroxide concentration constant at 2 molar. The slag content was evaluated at 5, 10, 15, 20, and 25 percent by weight

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of dry soil to determine the optimal percentage that yields the greatest enhancement in soil strength. The use of 2 molar sodium hydroxide allowed for the investigation of the effects of ground granulated blast furnace slag independently, without the influence of excessive alkali activation. From the findings, the most effective slag percentage was selected for the next stage.

In the second phase, the concentration of sodium hydroxide was adjusted while maintaining a constant optimum percentage of ground granulated blast furnace slag. The sodium hydroxide solution was evaluated at concentrations of 2, 4, 6, 8, 10, 12, and 14M to investigate its impact on geopolymerization and strength enhancement. The objective was to identify the ideal activator concentration that optimizes soil stabilization without causing excessive brittleness or issues with workability. The optimal sodium hydroxide concentration determined in this phase was utilized for the final step.

In the third and concluding phase, coir fiber was incorporated into the mixture while keeping both the ground granulated blast furnace slag and sodium hydroxide concentration at their previously established optimum levels. Coir fiber was added in varying proportions of 0.5, 1, 1.5, and 2 percent by weight of dry soil to evaluate its effect on ductility and tensile strength. The aim was to determine the coir fiber content that improves the soil's performance without jeopardizing its structural integrity.

By adhering to this systematic approach, the research provided a thorough assessment of the impacts of each stabilizing element, culminating in the selection of an optimized geopolymer mixture for soil stabilization.

VII. TESTING AND EVALUATION

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To assess the effectiveness of geopolymer-stabilized soil, a range of laboratory tests were carried out to evaluate its mechanical and geotechnical properties. The testing phase comprised the Unconfined Compressive Strength (UCC) test, the California Bearing Ratio (CBR) test, and the Atterberg Limit test, all conducted under specific conditions to examine the effects of various mix proportions and curing methods.

The Unconfined Compressive Strength (UCC) test was performed to evaluate the compressive strength of the stabilized soil samples under various curing conditions. The samples underwent testing after being subjected to 24 hours of oven curing at 70°C, along with 7-day, 14-day, and 28-day ambient curing. This test offered valuable insights into the strength development over time and the effects of sodium hydroxide concentration and coir fiber reinforcement on the soil's load-bearing capacity. Elevated strength values signified successful geopolymerization and enhanced soil stabilization.

The California Bearing Ratio (CBR) test was conducted to evaluate the load-bearing capacity of the geopolymer-treated soil, especially for potential applications in subgrade and pavement. This test was performed solely for the optimal mix compositions that were identified.

The Atterberg Limit test was executed to assess the impact of geopolymer stabilization on the soil's consistency and plasticity. The Liquid Limit (LL), Plastic Limit (PL), and Shrinkage Limit (SL) tests were carried out using the same optimal mix proportions applied in the CBR test. These tests yielded crucial data on the behavior of geopolymer-treated soil under different moisture conditions, which is vital for comprehending its long-term stability and suitability for construction purposes.

Through the execution of these tests, the study provided a thorough assessment of the mechanical performance and durability of geopolymer-stabilized soil, resulting in a dependable understanding of its effectiveness in soil improvement applications.

UCC Test Results

In the initial phase of the experimental plan, the content of Ground Granulated Blast Furnace Slag (GGBFS) is adjusted from 5% to 25%, while keeping the NaOH concentration constant at 2M. The GGBFS percentage is increased at regular intervals, specifically 5%, 10%, 15%, 20%, and 25%. For each specified proportion, the soil is thoroughly combined with GGBFS and NaOH solution to guarantee an even distribution of the stabilizing agents.

Once prepared, the samples are subjected to the Unconfined Compressive Strength (UCC) test to assess the effect of varying GGBFS percentages on soil strength. The results of the test are examined to identify the optimal GGBFS content that yields the maximum strength and stability. This ideal percentage is then applied in the subsequent phase of the study, where the NaOH concentration is modified to further improve soil stabilization.

TABLE 3 UCS VALUES OF VARYING GGBFS PERCENTAGES AND NAOH MOLARITIES

Mix ID	Untreated Soil (%)	GGBFS (%)	NaOH (M)	UCS Value (kN/m^2)
M1	95	5	2	26.48
M2	90	10	2	29.42
M3	85	15	2	47.07
M4	80	20	2	58.83
M5	75	25	2	37.75

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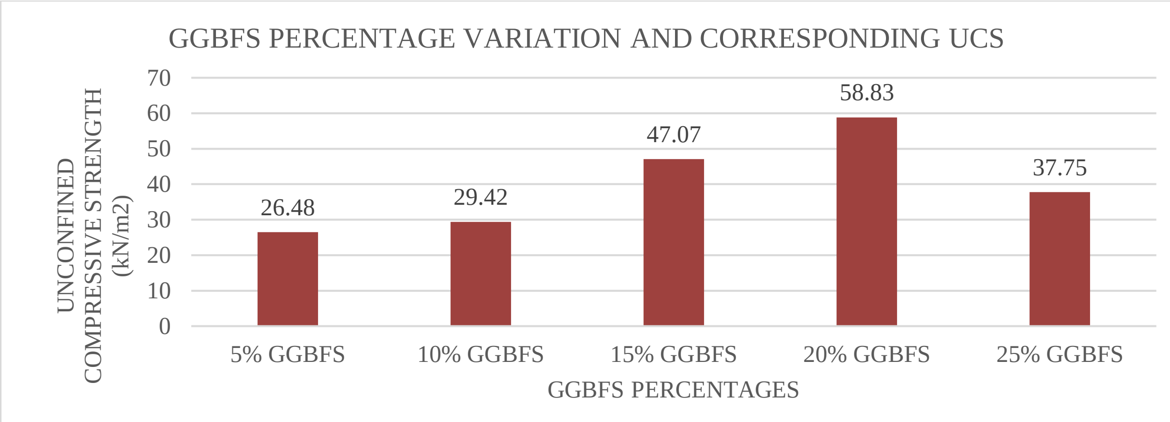

Fig.1 GGBFS percentage variation and corresponding UCS

According to the experimental findings, it was noted that the soil samples treated with different percentages of Ground Granulated Blast Furnace Slag (GGBFS) showed a gradual enhancement in strength characteristics up to a specific threshold. Among the samples evaluated, the mixture with 20% GGBFS exhibited the highest unconfined compressive strength (UCC) and overall stability. This suggests that at this particular percentage, the geopolymerization reaction between GGBFS and the alkaline activator (NaOH) was most efficient, resulting in improved bonding within the soil matrix. Consequently, 20% GGBFS was recognized as the optimal dosage, as it led to a significant enhancement in the mechanical properties of the soil without compromising workability or causing material wastage.

TABLE 4 UCS VALUES OF VARYING NAOH MOLARITIES AND OPTIMUM GGBFS PERCENTAGES

Mix ID	Untreated Soil (%)	GGBFS (%)	NaOH (M)	UCS Value (kN/m^2)
M6	80	20	2	58.83
M7	80	20	4	65.21
M8	80	20	6	71.58
M9	80	20	8	81.39
M10	80	20	10	89.24
M11	80	20	12	74.53
M12	80	20	14	68.64

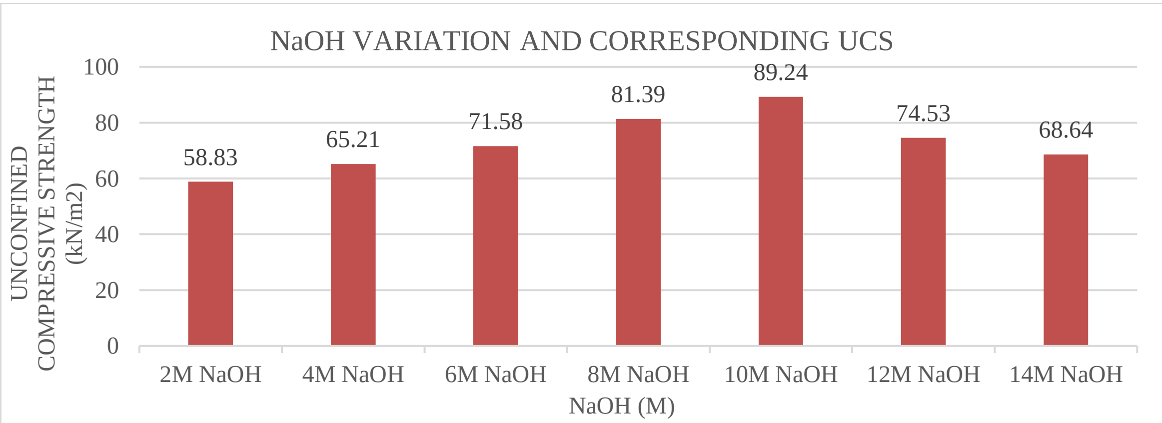

Fig 2 NaOH variation and corresponding UCS

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Based on the test outcomes, the ideal sodium hydroxide (NaOH) concentration was found to be 10M, as it produced the maximum unconfined compressive strength and enhanced overall stability of the geopolymer-treated soil. The increase in NaOH molarity initially improved the activation of GGBFS, thus facilitating more effective geopolymerization and superior bonding within the soil structure. However, beyond 10M, no notable strength increase was recorded, and in some instances, slight decreases were observed, potentially due to excessive alkalinity disrupting the gel structure or causing efflorescence. Therefore, 10M NaOH is deemed the most effective concentration for achieving optimal mechanical performance.

TABLE 5 UCS VALUES OF OPTIMUM GGBFS PERCENTAGE, OPTIMUM NAOH MOLARITIY AND VARYING COIR FIBER

Mix ID	Untreated Soil (%)	GGBFS (%)	NaOH (M)	Coir Fiber (%)	UCS Value(kN/m^2)
M13	80	20	10	0.5	92.18
M14	80	20	10	1	99.04
M15	80	20	10	1.5	85.18
M16	80	20	10	2	78.45

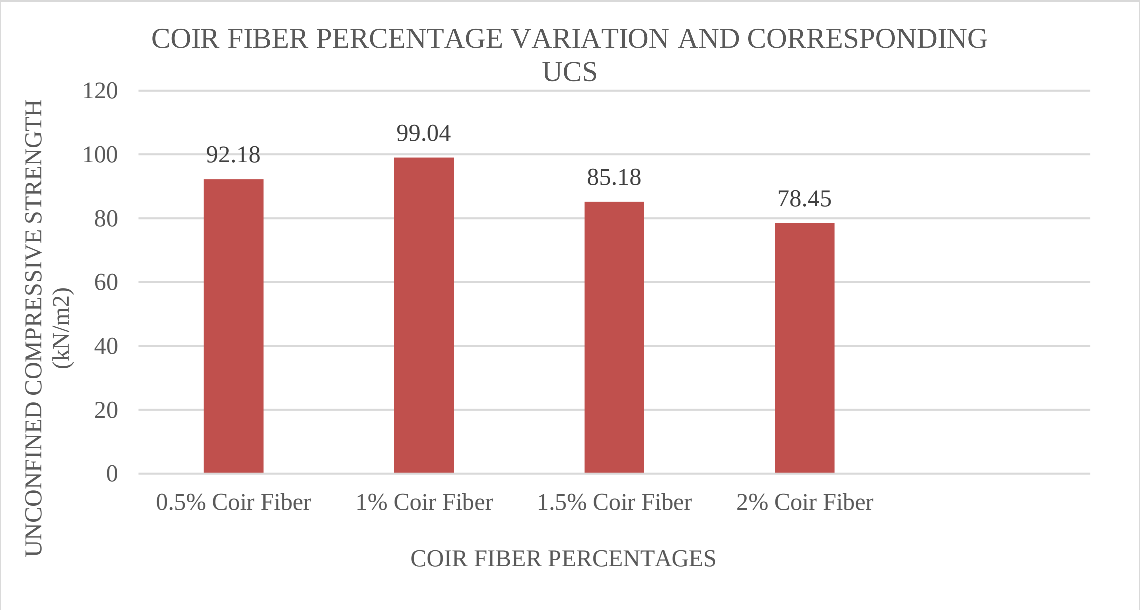

Fig.3 Coir Fiber percentage variation and corresponding UCS

TABLE 6 COMBINED UCS VALUES OF OPTIMUM MIXES

Mix	Untreated Soil (%)	GGBFS (%)	NaOH (M)	Coir Fiber (%)	UCS Values(kN/m^2)
M4	80	20	2	0	58.83
M10	80	20	10	0	89.24
M14	80	20	10	1	99.04

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The M4 mix which consists of 80% soil, 20% GGBFS, 2M NaOH, and zero coir fiber, resulted in a UCS value of 58.83 kN/m². In contrast, the M10 mix is made up of 80% soil, 20% GGBFS, 10M NaOH, and also lacks coir fiber, yielded a UCS value of 89.24 kN/m². While the M14 mix, which contains 80% soil, 20% GGBFS, 10M NaOH, and 1% coir fiber, achieved the highest UCS value of 99.04 kN/m². Thus, it can be concluded that the mix with GGBFS, NaOH, and coir fiber (M14) provided the maximum UCS value and is regarded as the best mix.

These mixes are chosen for further evaluation to analyze the effect of incorporating the constituents on soil's bearing capacity, plasticity and shrinkage by CBR tests and Atterberg Limit tests.

CBR Results

In the subsequent phases of the research, the California Bearing Ratio (CBR) test will be performed to assess the load-bearing capacity of the three optimal geopolymer-stabilized soil samples. The chosen samples consist of (1) 20% GGBFS with 2M NaOH, (2) 20% GGBFS with 10M NaOH, and (3) 20% GGBFS with 10M NaOH and 1% coir fiber. These samples were selected based on their performance in earlier Unconfined Compressive Strength (UCC) tests, which identified the ideal proportions of GGBFS and NaOH, followed by the incorporation of coir fiber to evaluate its reinforcing impact.

The CBR test plays a crucial role in evaluating the load-bearing capacity of stabilized soil, especially in the context of road subgrades and pavement structures. This study seeks to analyze the impact of higher NaOH concentration and coir fiber reinforcement on the soil's resistance to penetration by comparing the CBR values of three optimal mixes.

The first sample (20% GGBFS + 2M NaOH) acts as the control, illustrating the effects of GGBFS stabilization at a lower NaOH concentration. The second sample (20% GGBFS + 10M NaOH) assesses the enhancement in soil strength due to the increased NaOH concentration, which promotes geopolymerization. Lastly, the third sample (20% GGBFS + 10M NaOH + 1% Coir Fiber) integrates natural fiber reinforcement to investigate its role in improving tensile strength, crack resistance, and overall stability.

TABLE 7 CBR VALUE FOR VARIOUS MIXES

Sample	CBR Value(%)
M0	1.4
M4	13.66
M10	19.30
M14	22.64

The results of the California Bearing Ratio (CBR) test indicate a significant improvement in soil strength following stabilization with geopolymer additives. The CBR value for the untreated soil was recorded at 1.4%, which reflects a low load-bearing capacity.

After stabilizing the soil with 20% GGBFS and 2M NaOH, the CBR value rose dramatically to 13.6%, underscoring the effectiveness of GGBFS and alkaline activation in enhancing soil strength. Furthermore, when the NaOH concentration was increased to 10M, the CBR value reached an even higher level of 19.3%, implying that a more robust alkaline environment promotes geopolymerization and soil stabilization.

Moreover, the addition of 1% coir fiber to the 20% GGBFS + 10M NaOH mixture further elevated the CBR value to 22.64%. This illustrates that coir fiber contributes to improved soil strength by bolstering its structural integrity and resistance to deformation. The synergistic effect of GGBFS, NaOH, and coir fiber demonstrates that geopolymer soil stabilization is an exceptionally effective and sustainable method for enhancing weak soils, thereby making them more appropriate for construction and pavement uses. The table below presents the CBR values achieved after stabilization.

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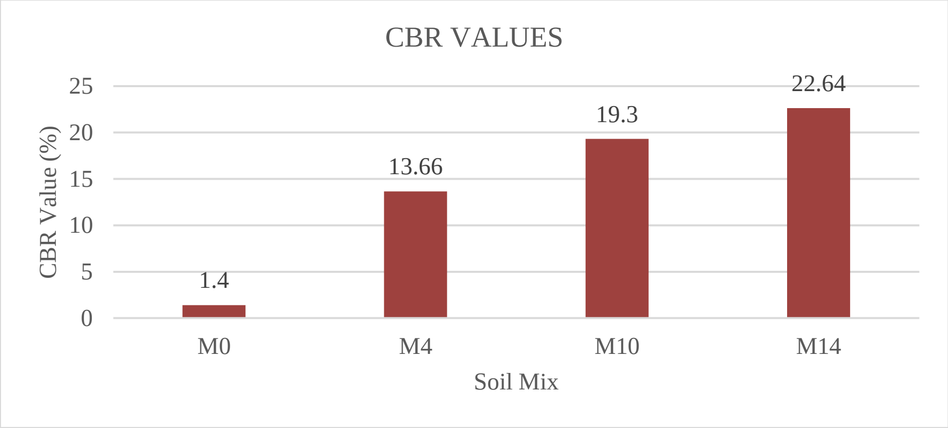

Fig 4 Comparison of CBR values

Plastic limit

The Plastic Limit (PL) test was conducted on soil incorporating optimal proportions of GGBFS, NaOH, and coir fiber to evaluate the effects of geopolymer stabilization on soil plasticity. This assessment identifies the minimum moisture level at which the soil can be shaped into thin strands without fracturing, offering valuable information regarding the workability and uniformity of the stabilized soil.

The initial sample analyzed, consisting of 20% GGBFS and 2M NaOH, signifies the ideal GGBFS ratio within the mixture. The stabilization properties of GGBFS and NaOH are anticipated to affect the plastic limit by modifying the soil's structure and decreasing its water retention ability. The subsequent sample, which includes 20% GGBFS and 10M NaOH, was evaluated to investigate the impact of heightened alkalinity on soil plasticity. An increased concentration of NaOH promotes geopolymerization, resulting in stronger connections among soil particles and a possible rise in the plastic limit.

Lastly, the third sample, comprising 20% GGBFS, 10M NaOH, and 1% Coir Fiber, was examined to assess the effect of coir fiber reinforcement on soil characteristics. Coir fibers enhance soil cohesion and particle interlocking, which may further influence the plastic limit. Through the execution of the Plastic Limit test on these samples, the research assesses the degree to which geopolymer stabilization improves soil performance, rendering it more appropriate for engineering applications that necessitate diminished plasticity and enhanced strength.

To carry out the test, a representative soil sample is air-dried and sieved to eliminate larger particles. A small quantity of the sample is then combined with water to create a plastic, moldable substance. This moist soil is divided into smaller sections, and each section is manually rolled into thin strands on a glass plate or a non-absorbent surface. The rolling process continues until the strand reaches a diameter of 3 mm, at which point it is examined for breakage. If the strand crumbles or breaks at this diameter, the moisture content at that moment is noted as the plastic limit.

The test is conducted several times, and the moisture content of the fractured soil threads is assessed by drying the samples in an oven at a temperature range of 105°C to 110°C. The ultimate plastic limit value is calculated as the mean moisture content of the samples that were tested.

TABLE 8 PLASTIC LIMIT OF VARIOUS MIXES

Sample	Plastic limit (%)
M0	25
M4	29
M10	31
M14	33

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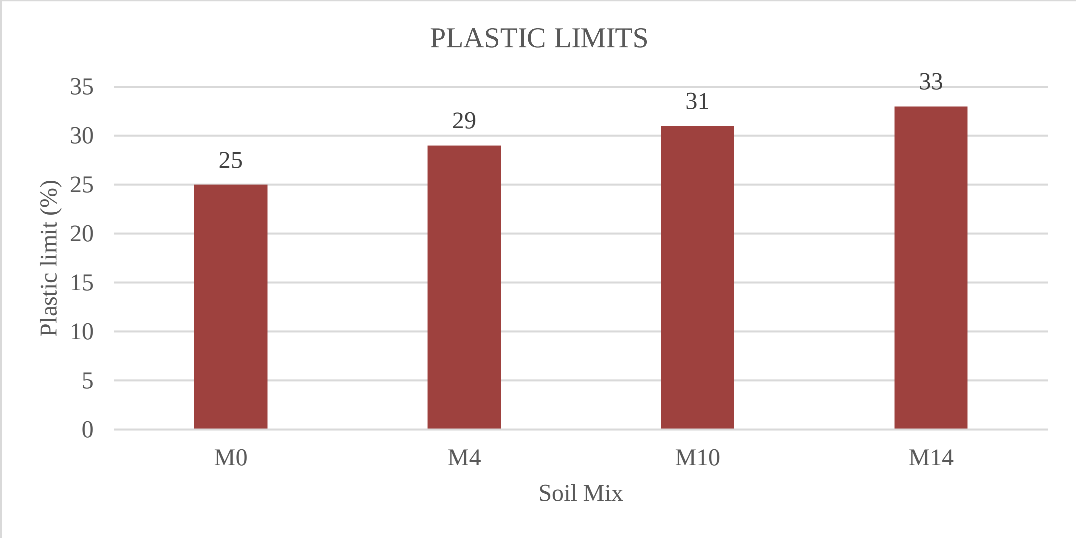

Fig 5 Comparison of Plastic limits

Liquid limit

The Liquid Limit test was conducted on soil incorporating optimal proportions of GGBFS, NaOH, and coir fiber. These samples were chosen due to their superior performance regarding strength and stabilization efficiency. The first optimal sample evaluated was 20% GGBFS combined with 2M NaOH, which signifies the ideal GGBFS content for soil stabilization. The second sample, consisting of 20% GGBFS and 10M NaOH, was selected for its ability to deliver the highest strength when the NaOH concentration was varied. Lastly, the third sample, which included 20% GGBFS, 10M NaOH, and 1% Coir Fiber, was tested to evaluate the effect of coir fiber reinforcement on the plasticity of the soil. By conducting the Liquid Limit test on these optimal samples, the research assesses the alterations in soil plasticity resulting from geopolymer stabilization, thereby aiding in the understanding of its applicability in construction projects.

The results of the Liquid Limit (LL) test reveal a gradual decline in the liquid limit as the soil undergoes stabilization with GGBFS, NaOH, and coir fiber. This decrease indicates an enhancement in soil characteristics, rendering it less plastic and more stable under varying moisture conditions.

The untreated soil displayed a higher liquid limit, signifying a stronger affinity for water and increased plasticity. Following stabilization with 20% GGBFS and 2M NaOH, the liquid limit was reduced, demonstrating the initial effects of geopolymerization in diminishing water absorption and enhancing soil structure. An additional increase in the NaOH concentration to 10M resulted in a more pronounced reduction in the liquid limit, indicating improved geopolymer bonding, which renders the soil less prone to volume changes induced by moisture.

TABLE 9 LIQUID LIMIT OF VARIOUS MIXES

Sample	Liquid limit(%)
M0	50
M4	46
M10	42
M14	40

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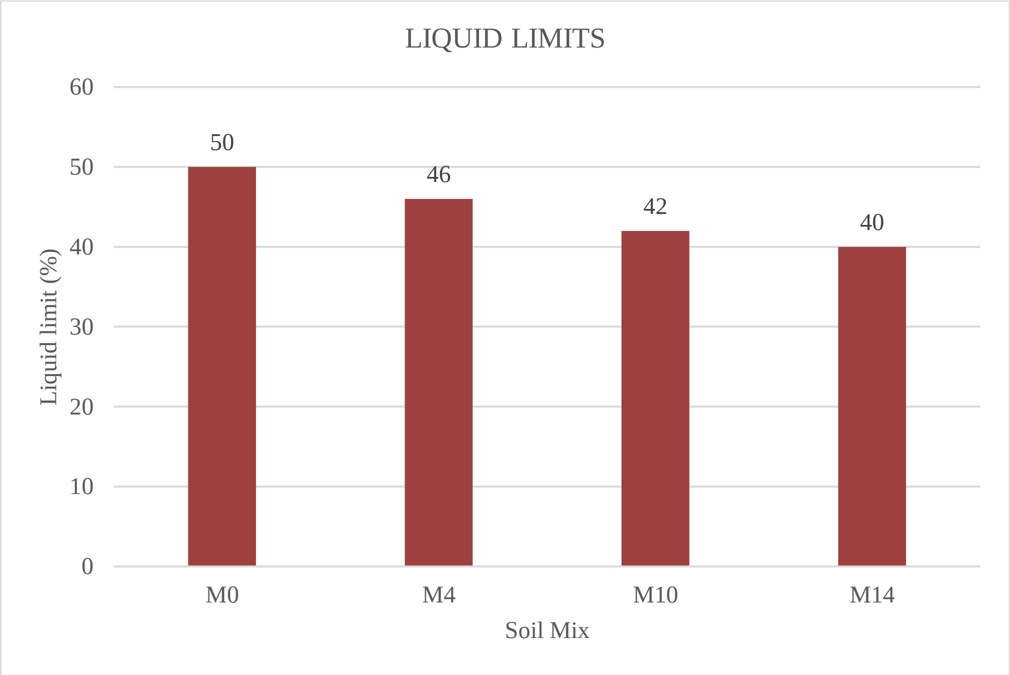

Fig 6 Comparison of liquid limits

Shrinkage Limit

The Shrinkage Limit test was conducted on soil incorporating optimal proportions of GGBFS, NaOH, and coir fiber to assess the impact of stabilization on the shrinkage characteristics of the soil. The shrinkage limit indicates the moisture content at which the soil ceases to reduce in volume with further drying. This parameter is vital for evaluating soil behavior under different moisture conditions, especially in construction and geotechnical contexts.

The selected optimum samples for the test comprised 20% GGBFS + 2M NaOH, recognized as the best mix based on variations in GGBFS, 20% GGBFS + 10M NaOH, which proved to be the most effective after adjusting NaOH concentration, and 20% GGBFS + 10M NaOH + 1% Coir Fiber, identified as the optimal mix following the addition of coir fiber. Analyzing these specific combinations aids in comprehending how each stabilization element contributes to reducing shrinkage and enhancing soil stability.

TABLE 10 SHRINKAGE LIMIT OF VARIOUS MIXES

Sample	Shrinkage Limit (%)
M0	23
M4	18
M10	15
M14	12

The shrinkage limit test was carried out to assess the decrease in volumetric changes of soil during drying for various stabilized mixes. The evaluation was conducted on the optimal samples derived from the unconfined compressive strength (UCC) test, which comprised ordinary soil, soil with the optimal GGBFS content (20% GGBFS + 2M NaOH), soil with the ideal NaOH concentration (20% GGBFS + 10M NaOH), and soil with the best coir fiber addition (20% GGBFS + 10M NaOH + 1% coir fiber). The shrinkage limit for each sample was measured to determine the impact of geopolymer stabilization and fiber reinforcement on the shrinkage characteristics of the soil. For ordinary soil, the shrinkage limit was recorded at 23%, indicating the natural propensity of the soil to lose volume when dried. With the addition of 20% GGBFS and 2M NaOH, the shrinkage limit decreased to 18%. This reduction signifies that the partial substitution of soil with GGBFS modified the interactions between soil particles, diminishing its water retention capacity and thereby reducing shrinkage. GGBFS aids in soil stabilization by generating cementitious compounds that improve soil cohesion, resulting in minimized volume changes during drying. When the NaOH concentration was raised to 10M while maintaining GGBFS at 20%, the shrinkage limit further declined to 15%. The higher NaOH concentration promotes the geopolymerization process, leading to the creation of more robust binding gels that effectively occupy the soil pores. This results in a more stable soil structure with reduced shrinkage tendencies. The increased alkalinity speeds up the dissolution of silicates and aluminates from GGBFS, facilitating the development of a denser geopolymer framework, which limits moisture loss and volume decrease during drying.

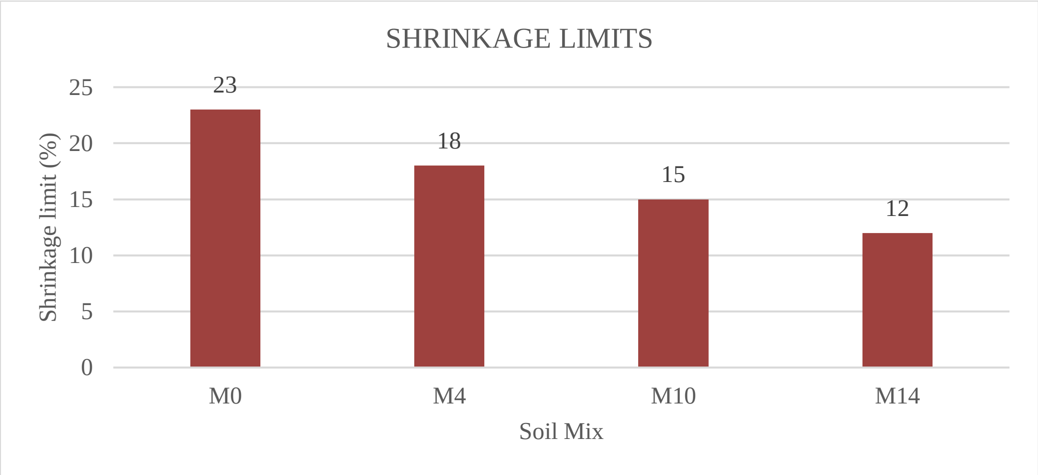

Fig 7 Shrinkage limits compared

As the concentration of NaOH was raised to 10M, while maintaining GGBFS at a constant 20%, the shrinkage limit further declined to 15%. The higher NaOH concentration promotes the geopolymerization process, resulting in the creation of more robust binding gels that more efficiently occupy the soil pores. This leads to a stiffer soil matrix with diminished shrinkage tendencies. The elevated alkalinity speeds up the dissolution of silicates and aluminates from GGBFS, aiding in the development of a denser geopolymer network that limits moisture loss and volume shrinkage during drying.

Ultimately, when 1% coir fiber was added to the mix of 20% GGBFS and 10M NaOH, the shrinkage limit dropped further to 12%, the lowest observed across all conditions tested. The inclusion of coir fiber likely mitigated shrinkage due to its role as a reinforcing agent within the soil structure. Coir fibers possess hygroscopic characteristics, allowing them to absorb and retain moisture, thus preventing significant volume fluctuations during the drying process. Moreover, the interlocking nature of the fibers within the geopolymer-stabilized soil matrix aids in minimizing shrinkage deformations, enhancing the soil's stability and reducing the likelihood of cracking.

The trend observed in the shrinkage limit values clearly demonstrates that geopolymer stabilization markedly decreases the soil's shrinkage potential. This effect becomes increasingly evident with higher NaOH concentrations and is further amplified by fiber reinforcement. A reduced shrinkage limit is advantageous for engineering purposes, as it lessens the chances of cracking, settlement, and deformation in structures constructed on treated soil. The findings indicate that the combination of GGBFS, NaOH, and coir fiber effectively stabilizes the soil, rendering it a viable method for enhancing soil durability and mitigating shrinkage-related issues in construction projects.

VIII. CURING

Curing is a crucial phase in the stabilization of geopolymer soil, as it significantly affects the development of strength and the durability of the treated soil. In this research, curing was performed solely on the final optimal mix: M14 (20% GGBFS + 10M NaOH + 1% Coir Fiber), which demonstrated the best results in prior strength evaluations. To evaluate the effects of curing, the samples underwent two different curing methods: oven drying at 70°C for 24 hours and ambient curing for periods of 7, 14, and 28 days.

One group of samples was subjected to oven drying at 70°C for 24 hours. This technique promotes rapid moisture evaporation, accelerating the geopolymerization process and resulting in early strength development. However, the swift reaction may lead to micro-cracking or incomplete geopolymerization if the moisture content decreases too rapidly.

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The outcomes from the Unconfined Compressive Strength (UCC) test for this group will help ascertain whether rapid curing improves or undermines the strength properties of the soil.

Another group of samples was cured at room temperature for varying lengths of time: 7 days, 14 days, and 28 days. In contrast to oven drying, ambient curing facilitates a gradual geopolymerization reaction, promoting better adhesion between the soil particles and stabilizing agents. Over time, the ongoing reaction of GGBFS with NaOH fortifies the soil structure, enhancing its durability and load-bearing capacity. The UCC test results at various curing intervals illustrate how strength development evolves over time and offer valuable insights into the long-term performance of the geopolymer-stabilized soil.

TABLE 11 UCS VALUES OF TREATED SPECIMEN UNDER VARIOUS CURING CONDITIONS

Curing conditions	UCS Values(kN/m^2)
7days at ambient temperature	110
14days at ambient temperature	118
28days at ambient temperature	130
24hours at 70°C	144

The unconfined compressive strength (UCC) of the soil sample that was cured for 7 days at room temperature was measured at 110 kN/m^2. This suggests that the geopolymerization process has made significant progress during the initial week, resulting in enhanced strength. The interaction between GGBFS, NaOH, and coir fiber plays a crucial role in improving soil bonding and stabilization. After 14 days of curing, the unconfined compressive strength of the soil sample increased to 118 kN/m^2.

The UCC of the geopolymer-stabilized soil showed an upward trend as the curing duration extended. For the sample that underwent curing at ambient conditions for 14 days, the UCC reached 118 kN/m^2, indicating a significant enhancement compared to the 7-day curing strength of 110 kN/m^2. This reflects that the geopolymerization reaction continues to evolve over time, resulting in a more stable and robust soil matrix. The UCC of the geopolymer-stabilized soil further increased with prolonged curing, achieving 130 kN/m^2 after 28 days of ambient curing.

This gradual strength enhancement underscores the long-term efficacy of geopolymerization in improving soil stability. In comparison to the UCC values of 110 kN/m^2 and 118 kN/m^2 from the 7-day and 14-day curing periods, respectively, the sample cured for 28 days demonstrated the highest strength. The observed strength gain over time can be linked to the ongoing polycondensation of the aluminosilicate gel, which fosters the development of a more compact and rigid geopolymer network. As curing progresses, excess moisture is gradually removed, leading to reduced pore spaces and enhanced particle bonding. The formation of stronger Si–O–Si and Si–O–Al linkages contributes to a denser, more durable structure with an increased load-bearing capacity. This improvement in strength indicates that the geopolymer-stabilized soil experiences continuous hardening over time, making it exceptionally suitable for long-term engineering applications.

The unconfined compressive strength (UCC) of the geopolymer-stabilized soil, which was subjected to oven drying at 70°C for 24 hours, reached 144 kN/m^2. This value surpasses the UCC measurements obtained for samples cured under ambient conditions for 7, 14, and 28 days. This finding suggests that oven drying significantly accelerates the geopolymerization process, resulting in rapid strength development in a short time frame.

The increase in UCC can be linked to the expedited removal of moisture, which enhances the polycondensation reaction of the aluminosilicate gel. The swift loss of water facilitates the creation of a dense and rigid geopolymer matrix, leading to a greater degree of bonding among soil particles. The Si–O–Si and Si–O–Al linkages form more quickly at elevated temperatures, which contributes to the early gain in strength.

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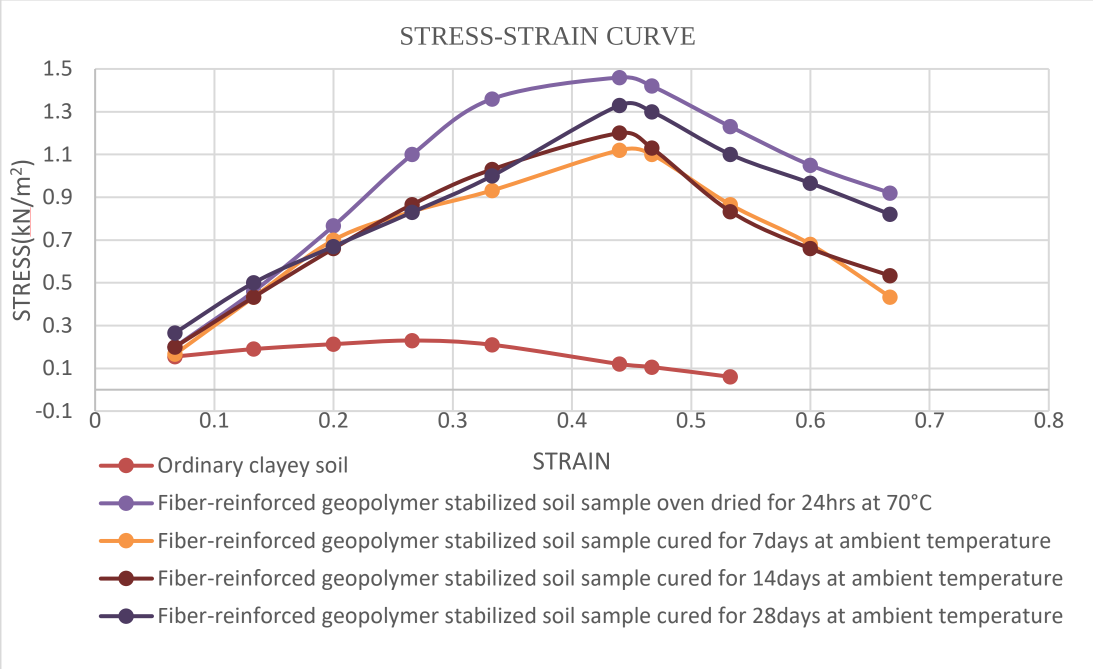

Graph 8.1 Stress-Strain curves of treated specimen under various curing conditions

IX. CONCLUSION

The study analyzed how variations in NaOH molarity, GGBFS concentrations, curing conditions, and coir fiber reinforcement affect the Unconfined Compressive Strength (UCC), California Bearing Ratio (CBR), and Atterberg Limits. The results are detailed below:

- The Unconfined Compressive Strength (UCC) recorded for 2M NaOH and 20% GGBFS was 58.83 kN/m², indicating a 160.8% increase in strength compared to untreated soil. Lower percentages of GGBFS (5%, 10%, 15%) did not provide enough geopolymer gel to effectively bind soil particles, resulting in decreased strength. Conversely, higher GGBFS percentages (over 20%) led to an excess of binder, creating an unstable or brittle geopolymer structure, which diminished UCC.

- With 20% GGBFS and 10M NaOH, the UCC rose to 89.24 kN/m², reflecting a 295.9% enhancement in soil strength. Lower NaOH concentrations (2M–8M) resulted in incomplete geopolymerization, which weakened soil stabilization. In contrast, higher concentrations (12M, 14M) resulted in excessive gel formation, causing brittleness and a reduction in strength. This indicates that 10M NaOH is the ideal concentration for achieving maximum strength while ensuring stability.

- The incorporation of 1% coir fiber into the optimal mix (20% GGBFS + 10M NaOH) further enhanced soil strength, yielding a UCC value of 99.04 kN/m², which corresponds to a 339.3% increase in strength compared to untreated soil. However, a lower fiber content (0.5%) did not offer adequate reinforcement, while an excessive fiber content (1.5% or more) resulted in poor fiber distribution, void formation, and matrix weakening, all contributing to a decrease in UCC.

- The curing conditions were essential for the development of strength. The peak UCC value of 144 kN/m² was achieved for the sample that was oven-dried at 70°C for 24 hours, demonstrating that thermal curing accelerates the geopolymerization process, resulting in a denser and stronger matrix. For samples cured at room temperature, UCC values rose with the duration of curing, reaching 110 kN/m² after 7 days, 118 kN/m² after 14 days, and 130 kN/m² after 28 days. This pattern confirms that extended ambient curing promotes geopolymerization, allowing the gel structure to mature and enhance strength.

- The CBR value for the optimal combination (20% GGBFS, 10M NaOH, and 1% coir fiber) was determined to be 22.64%, which is considerably higher than that of untreated soil. This enhancement is due to the improved geopolymerization reaction, which boosts soil strength and stability. The inclusion of coir fibers further aided by enhancing tensile strength, crack resistance, and stress distribution, resulting in a denser, more durable, and dimensionally stable soil capable of withstanding deformation under load.

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- The Atterberg Limit tests were performed to assess soil plasticity and moisture sensitivity. The Plastic Limit (PL) of the fiber-reinforced geopolymer soil was 33%, indicating better workability and decreased brittleness. The Liquid Limit (LL) was measured at 40%, suggesting that the stabilized soil is less susceptible to moisture-induced instability. The Shrinkage Limit (SL) was noted as 12%, which improves dimensional stability, lowers shrinkage potential, and reduces the risk of cracking. The synergistic effect of the geopolymer binder and coir fiber reinforcement is vital in minimizing plasticity and shrinkage, making the stabilized soil more resilient to environmental changes.

The findings indicate that the stabilization of soil through geopolymer methods utilizing GGBFS and NaOH greatly improves soil strength, durability, and workability. Furthermore, incorporating coir fibers enhances performance by boosting tensile strength, flexibility, and resistance to shrinkage and cracking. The results affirm that the ideal combination of 20% GGBFS and 10M NaOH, along with 1% coir fiber, serves as an effective technique for soil stabilization, making it suitable for road subgrades, foundations, and various construction applications that demand high-strength, stable soil.

REFERENCES

[1]. Syafiadi Rizki Abdila, Romisuhani Ahmad, Mohd Mustafa Al Bakri Abdullah, Dumitru Doru Burduhos Nergis, Shayfull Zamree Abd Rahim, Mohd Firdaus Omar, Andrei Victor Sandu, Petrica Vizureanu, Syafwandi. “Potential of Soil Stabilization Using Ground Granulated Blast Furnace Slag (GGBFS) and Fly Ash via Geopolymerization Method: A Review” Materials 2022, 15, 375

[2]. Mukhtar Hamid Abed, Firas Hamid Abed, Seyed Alireza Zareei, Israa Sabbar Abbas, Hanifi Canakci, Nahidh H. Kurdi, Alireza Emami. “Experimental feasibility study of using eco- and user-friendly mechanochemically activated slag/fly ash geopolymer for soil stabilization” Cleaner Materials Volume 11, March 2024, 100226

[3]. S.C. Boobalan, M. Sivakami Devi. “Investigational study on the influence of lime and coir fiber in the stabilization of expansive soil” Materialstoday proceedings Volume 60, Part 1, 2022, Pages 311-314

[4]. Ehsan Kasehchi, Mohammad Ali Arjomand, Mohammad Hadi Alizadeh Elizei. “Experimental investigation of the feasibility of stabilizing inshore silty sand soil using geopolymer based on ceramic waste powder: An approach to upcycling waste material for sustainable construction” Case Studies in Construction Material Volume 20, July 2024, e02979