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Properties of Slag-Based Geopolymer-Stabilized Indian Lithomargic Soil Using Sugarcane Bagasse Ash for Sustainable Pavement Design

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Abstract: This investigation examines the feasibility of stabilizing lithomargic soil subgrades through the utilization of geopolymerized slag (GGBS) and sugarcane bagasse ash (SCBA). Through a series of compaction experiments, the best dry density was obtained by maintaining a constant slag dosage of 10% by weight of the soil while altering the dosage of SCBA. The geopolymeric aqueous solution is produced by combining water glass (Na_2SiO_3) and caustic soda (NaOH). The soil mixtures were subjected to both unstabilized and stabilized UCS and CBR experiments. The experiments suggest that the strength of subgrade soil enhances with the inclusion of SCBA up to a specific threshold (i.e., 15%), after which it decreases due to a constant dosing of slag. In order to comprehend the hardening performance subsequent to geopolymer stabilization, the microstructural analysis is implemented. The establishment of co-relationships among the strength parameters (UCS and CBR) facilitated the formulation of a simple linear regression model in order to comprehend the relationship among the strength parameters of geopolymer-stabilized lithomargic soil. The long-term effectiveness of mechanical performance was disclosed by the boost of strength performance, as evidenced by the prolonged CBR and UCS achievement. This study also suggests a pavement design that adheres to the Indian Roads Congress principles for low-volume roadways, which results in a substantial reduction

(45%) of entire pavement thickness while maintaining performance. The economic benefits of geopolymer stabilization in rural pavement construction were revealed through a comprehensive cost analysis that compared the conventional and modified pavement designs while also maintaining the sustainability element.

Keywords: geopolymer; sustainability; unconfined compressive strength; sugarcane bagasse ash; stabilization; CBR; pavement design.

1 Introduction

The increasing amounts of heavy traffic and persistent environmental conditions have resulted in considerable obstacles for the building of conventional roadways. These additional stresses result in a reduced lifetime of the pavement structures. Consequently, there is an ongoing pursuit of new construction methods to resolve these challenges and attain optimum pavement performance. The soil subgrade is universally regarded as the most critical layer for maintaining the overall stability of pavement constructions [1]. Subgrade stabilization is widely used to improve mechanical performance and alter the characteristics of poor foundation soil [2]. A range of stabilizing agents is used, including cementing agents, electromechanical stabilizers, industrial by-products, and chemical substances. Employing locally sourced discarded materials in stabilization initiatives might reduce the trash disposal challenges faced by local governments. Urban planners have considerable challenges in managing industrial waste, attributed to the escalating amount of demolition debris, limited trash disposal locations, increased transportation and trash disposal expenses, and heightened apprehensions about pollution and destruction of the environment [3–5]. The synthesis of “geopolymers” from industrial by-products has become a significant research priority owing to its promise to provide a cost-efficient and environmentally

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sustainable cement-like material. The chemical activation of desiccated materials, such as fly ash and slag, in an alkaline environment entails a chemical process that converts glassy systems, which are partially or entirely meta-stable and/or amorphous, through an intensely compact, bonded stabilizing product [6]. This study explores a novel and environmentally sustainable approach to soil modification.

In the present investigation, a form of agro-waste known as sugarcane bagasse ash (SCBA) and an industrial spin-off known as “ground-granulated blast furnace Slag” (GGBS) are used in order to produce geopolymeric cementing agents for the purpose of stabilizing the soil. The region of Dakshina Kannada in the state of Karnataka is the primary source of lithomargic soils. Lithomargic soil, also known as “shedi” soil, is prominent along the western coastline of southern India. This kind of soil presents considerable issues owing to its high water sensitivity and severe loss of strength when it becomes saturated. These types of soils, which are often categorized as silty sand or sandy silt with a significant silt component, are prone to a variety of problems, such as slope instability, base failures, barrier collapses, and unequal settlements. Because of this, stabilizing soils of this kind is necessary in order to satisfy engineering requirements [1].

There are just a few research studies that have been conducted on the use of geopolymers in the alteration of soil that is being considered. In light of this, an effort was made in the present time to create GGBS and SCBA as binding compounds and to dynamically activate the binders by means of the alkaline environment. Within the scope of this article, the stabilizing process of the lithomargic (shedi) soils that are readily accessible in the area was documented. Ordinary portland cement (OPC) has been shown to be an excellent main addition for stabilizing lithomargic and lateritic soils, as evidenced by a number of research studies [7–9] [10]. These studies have achieved successful application to the recommended standards. This binding process is also seen with geopolymer binder-based cements made when they are treated with granular soils [2,5,12]. The primary effect of the incorporation of OPC is to assist the cementing of personage soil particles, which ultimately results in the chemical stability of the initial soil [11]. As a result, the primary purpose of this investigation is to seek out the influence that geopolymeric slag (i.e., GGBS) and SCBA have on the characteristics of lithomargic soils by means of geotechnical analysis for the sake of pavement engineering subgrade applications.

2 Materials and Experimental Methodology

The lithomargic soil that was utilized for the investigation was collected from the Nitte area in the state of Karnataka, which is located at 1301.09 degrees north and 740.62 degrees east. A visual representation of the shedi's primary geotechnical characteristics is shown in Figure 1. Jindal Steel Works (JSW) in Toranagallu, Karnataka, was the source of the GGBS that was used for this examination. The GGBS is the key precursor binder that is used in the creation of geopolymer. Jamnagar, Gujarat, was the location of the supplier from which the SCBA was obtained.

One of the local dealers was able to provide all the chemicals that were required for geopolymerization. These chemicals included NaOH solids and fluid Na_2SiO_3 . For the preparation of the aqueous GP solution, water from the lab's taps was used. A visual representation of the characteristics of the primary components (GGBS and SCBA) as well as the specifics of the GP preparations could be seen in Figure 2. Checks were carried out in accordance with the proper Indian standard codes of practice in order to determine the impact that the GP had on the geo-aspects during the investigation.

Initially, the preliminary geotechnical tests on the shedi soils were performed. From the groundwork studies, the best dosage of “activator modulus” (Ms value, i.e., $\text{SiO}_2/\text{Na}_2\text{O}$ ratio) and “ Na_2O -to-binder” ratio were derived from literature studies [13,14]. The essential information is delineated under GP in Figure 2. The water-to-GP precursor proportion was maintained at 0.25 over the whole study. The total binder doses were systematically increased from 10% to 30% in increments of 5%, and the compaction characteristics were analyzed. Taxonomy “G” denotes the mixture, while the suffix digit signifies the percentage of SCBA relative to the mass of the earth; specifically, G-10 refers to soil mixed with 10% geopolymer binder. G-0 denotes natural (unstabilized) lithomargic soil. Moreover, in each mixture, the GGBS content was always kept at 10% of the total binder based on our prior study on the same soil, while the SCBA concentration was increased in 5% increments (up to 20%) from an initial 0%. For instance, in the G-20 mix, the composition included 10% GGBS and 20% SCBA, respectively. For all mixtures, the IS light compaction test, CBR, and UCS evaluations were conducted, and the results were recorded as an average of three consecutive specimen tests, ensuring that the standard variation

Specific Gravity	Plasticity	IS Light Compaction	IS Classification	Permeability (k)	UCS value	Soaked CBR
2.32	LL= 59.3 % PL=29.7 % SL= 27.1 %	OMC= 20.68 % MDD = 1.51 g/cc	MH	9.21×10^{-9} cm/s	93 kPa	2.40 %
IS 2720-3: 1980	IS 2720-5: 1985; IS:2720-6: 1972	IS 2720-7: 1980	IS 1498: 1970	IS:2720-17:1987	IS 2720-10: 1991	IS: 2720-16:1987

Figure 1: Basic properties of pure lithomargic soil.

Geopolymer Solution	Sugarcane Bagasse Ash	Ground-Granulated Blast Furnace Slag
- Combination of calculated amount of NaOH, Na_2SiO_3 and Water - NaOH flakes with 97% purity - Activator modulus (ratio of SiO_2 to Na_2O i.e., Ms) of $\text{Na}_2\text{SiO}_3 = 2.23$ GP Preparation Specifications: Na_2O dosage of 4.0% of total binder content. - Specific Gravity = 1.40 - Activator modulus (Ms) = 1.25	- Specific Gravity = 2.28 % Finer than 90μ Sieve = 99.3 % - The specific surface area = 1.79 m^2/g - Loss on Ignition (LoI) = 1.12 % - Major Chemical Composition: - Silica (SiO_2) = 58.50 % - Lime (CaO) = 12.80 % - Alumina (Al_2O_3) = 15.07 % - Iron Oxide (Fe_2O_3) = 4.01 %	- Specific Gravity = 2.89 % Finer than 90μ Sieve = 100 % - The specific surface area = 0.36 m^2/g - Loss on Ignition (LoI) = 0.24 % - Major Chemical Composition: - Silica (SiO_2) = 38.12 % - Lime (CaO) = 36.89 % - Alumina (Al_2O_3) = 14.52 % - Iron Oxide (Fe_2O_3) = 1.15 %

Figure 2: Properties of stabilizing additives used for the production of geopolymer.

among individual sample results did not exceed 15%. Extended UCS and CBR tests were conducted on selected samples to assess the long-term impact of stabilization [15]. The highway design and preliminary cost analysis were developed in accordance with the IRC guidelines for low-traffic roads, namely, IRC: SP:62 for concrete (rigid) pavements [16] and IRC: SP:72 for the bituminous pavement counterparts [17]. An analysis of linear regression was conducted to examine the relationship between the UCS and CBR of the stabilized soil, as well as to understand the effects of stabilization on these two critical soil characteristics [18]. The stabilized soil for the optimal blend was subjected to microstructure analysis to better understand the hydration mechanism of ground improvement [10]. **Figure 3** presents the materials and major experimentation glimpses carried-out as a part of the laboratory investigation.

3 Results and Discussions

3.1 Compaction Properties of GP-Stabilized Lithomargic Soil

Figure 4 displays the outcomes of the IS light compaction tests, presented as the average values after all three experiments for the GP-stabilized lithomargic soil mixtures at different SCBA proportions. The results demonstrate that when the SCBA dose rises, the “maximum unit-weight” (MDD) of the mixture first climbs to a certain threshold, beyond which further additions of SCBA result in a decline in the MDD peak. Conversely, the “Optimum Water Content” (OMC) of the mixture exhibited no discernible pattern. The augmentation of cement dosage prompted the soil granules to shift from a loosely aggregated structure to a tightly bound configuration,

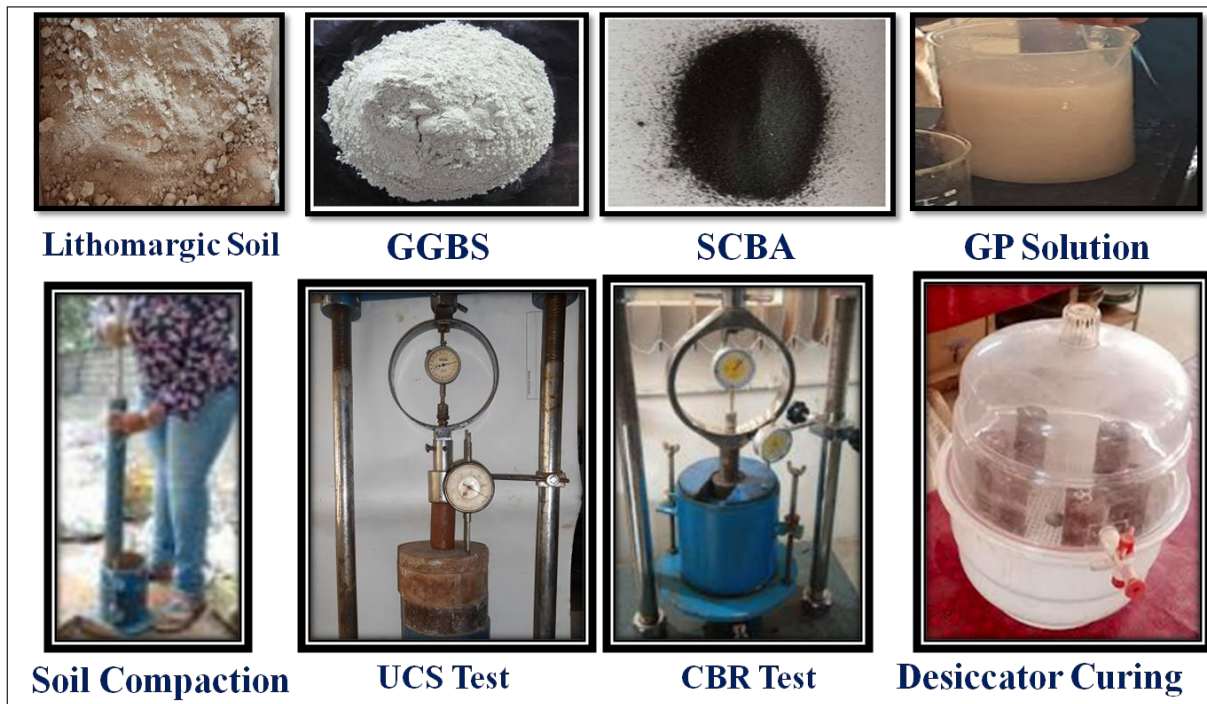


Figure 3: Materials and glimpses of laboratory experimentations.

leading to altered water needs for achieving optimal compaction. The test findings indicated that lithomargic soil attained its maximum MDD with a 15% SCBA dose and a 10% GGBS binder in the face of GP solution. Compared to the mixes without admixes, there was an 18% augment in MDD for the stabilized soil.

The enhancement in Proctor density for the lithomargic soil treated with geopolymer cement containing 10% GGBS and varying proportions of SCBA, activated with a GP solutions, can be explained by several interrelated mechanisms that have been documented in the literature. The initial increase in MDD with the addition of GGBS and SCBA can be attributed to the reaction of alumino-silicate materials. As reported by Davidovits [19] and further elucidated by Duxson et al. [20] and Provis and Van Deventer [21], the presence of alkaline activators promotes the dissolution of alumino-silicates, leading to the formation of a dense 3D alkali alumino-silicate network. This network, predominantly composed of amorphous gel phases, fills the voids within the soil matrix, thereby increasing the soil matrix density at a given compactive effort. The careful balance of silica and alumina in the mix is considered crucial as it dictates the structure and stability of the resultant GP gel. As the SCBA content increases up to 15% in the presence of constant 10% GGBS, the optimum Si/Al ratio is achieved, facilitating the formation of stable C-S-H like C-A-S-H (or N-A-S-H) gels,

which further enhance the soil's compactness and density [22]. The increased density at this stage can also be explained by the ionic exchange mechanism, where the Ca^{2+} ions introduced by GGBS reduce the thickness of the diffused double-layer surrounding soil particles, thereby promoting flocculation and better particle packing [23]. This leads to an improvement in the mechanical interlocking between soil particles, manifesting as an increase in the value of maximum Proctor density.

However, beyond the optimal dosage, here specifically after 15% SCBA (and 10% GGBS), the MDD begins to decrease. This decline can be attributed to several factors. First, the excessive addition of SCBA may disrupt the optimal Si/Al ratio, leading to an imbalance in the GP gel formation. When the Si/Al ratio deviates from the optimal range, the structure of the alumino-silicate network may become less stable, potentially resulting in the formation of less dense or more porous phases. Additionally, the introduction of too much SCBA can lead to an increase in unreacted and/or partially reacted particles within the stabilizer matrix. This excessive presence of nonreactive materials may prevent the full densification of the soil matrix, reducing the effectiveness of compaction, at a constant compactive effort. The hydration process in such a scenario may also become less efficient, as the available GP activators might become insufficient to fully react with the increased SCBA content, leading to incomplete alkali

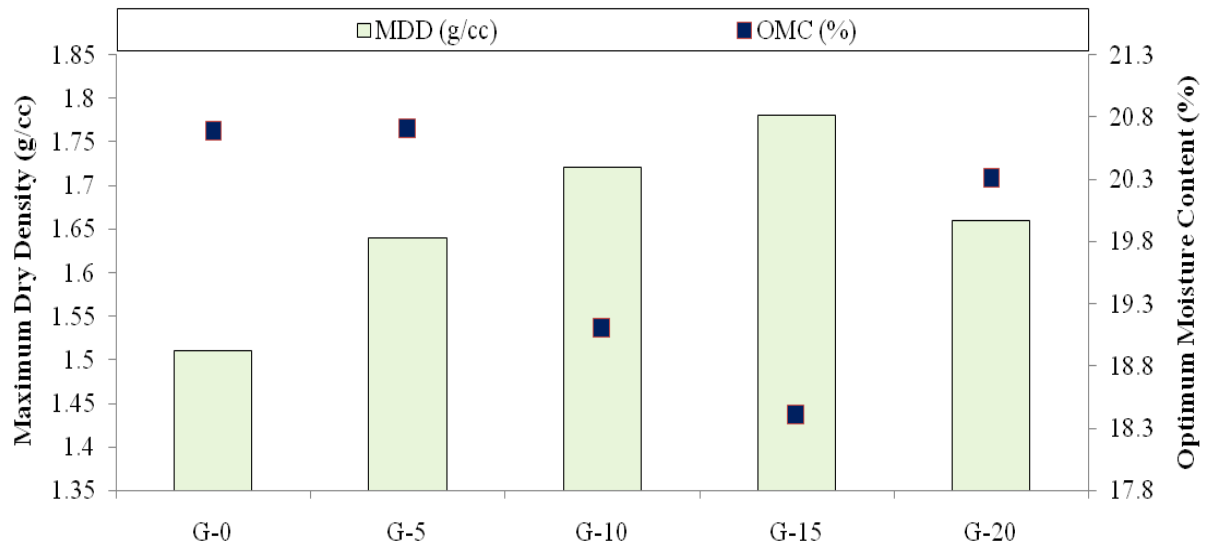


Figure 4: Outcomes of IS light compaction upon geopolymer stabilization at different SCBA amount.

activation [24]. This can result in a matrix with reduced cohesiveness, which would negatively impact the MDD.

3.2 UCS and CBR of GP-Stabilized Lithomargic Soil and Their Interrelationships

The UCS and soaked CBR tests were executed on all blends with diverging SCBA dosages. **Figure 5** shows the upshots, indicating that the CBR value could augment by up to 35.9 times and the UCS rate by approximately 5.47 times with the addition of 10% GGBS-based GP containing 15% SCBA with insinuation to the virgin shedi soil. These enhancements in geotechnical performance are likely due to the development of the “postpeak potency” of the stabilized earth, connected with a decline in stiffness. The previous study has similarly reported a decline in strength performance with increased stabilizer dosage, attributed to a decrease in the “elastic vigor aptitudes” of the modified soil [25]. The increased strength performance observed with GP stabilization can also be attributed to the reaction between the CaO content in the binder and the aluminates and silicates existing in the alkali-activating chemical solutions. This reaction leads to the formation of calcium aluminosilicate hydrates, as documented by previous researchers [26–28].

Further, the increase in UCS and CBR values observed at 10% GGBS and 15% SCBA, in comparison to the unstabilized soil, is a direct consequence of the improved soil matrix density, chemical bonding, and particle interactions facilitated by the GP treatment. As discussed

in the compaction results, the alkali activation of GGBS and SCBA leads to the dissolution of aluminosilicate materials, forming a dense, 3-D network of amorphous aluminosilicate gels ([19][20][21]). This network not only enhances the density but also significantly improves the soil’s mechanical properties. At 15% SCBA, the Si/Al ratio is optimal, resulting in the formation of a well-connected and stable gel structure that binds the soil particles together more effectively, thereby increasing the UCS to 5.5 times and the soaked CBR to 36 times when compared with the unstabilized soil matrix. The dense and cohesive matrix developed at this stage provides better resistance to deformation under load, which is reflected in the higher strength values. The compactness combined with the strength of the GP bonds contributes to this enhanced strength. As explained by Liew et al. [22] and Ho et al. [29], the C-A-S-H/N-A-S-H gels are known for their superior binding properties, which are responsible for the significant improvements in strength. At the optimal 15% SCBA content, these gels fill the voids between soil particles, reducing porosity and creating a more rigid matrix. This enhanced gel formation is also a key factor in the observed increase in CBR values, as the soil’s ability to resist penetration under load is greatly improved.

Further, the reduction in UCS (and CBR) beyond 15% SCBA parallels the trends observed in the compaction results. Beyond the optimal dosage, the excess SCBA likely disrupts the ideal Si/Al ratio, leading to the formation of weaker gel phases or crystalline products that do not contribute as effectively to strength. The presence of unreacted or/and partially reacted SCBA particles may

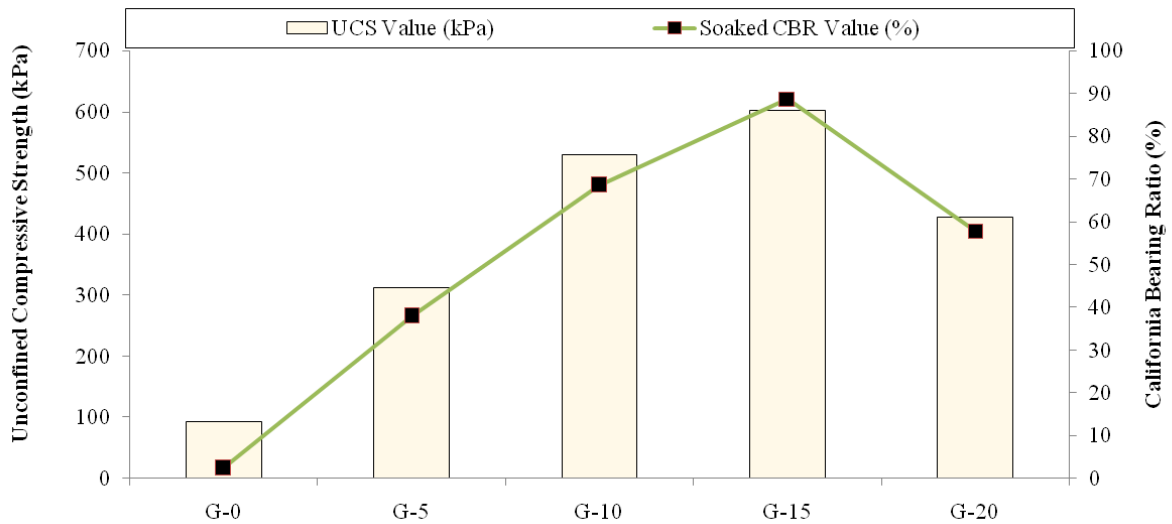


Figure 5: Results of CBR and UCS upon geopolymer stabilization at various SCBA dosages.

introduce discontinuities within the soil matrix, reducing the overall strength and penetration-resistivity capacity of the soil [24].

Further, understanding the relationship between UCS and CBR is pivotal in soil stabilization, as it enables a more holistic assessment of the mechanical properties of GP-treated lithomargic soil. Although both UCS and CBR are fundamental indicators of soil strength, they assess different aspects, that is, the UCS measures the soil's capacity to endure unconfined compressive loads, while CBR evaluates the soil's resistance to penetration, typically under conditions simulating traffic loads. Establishing a strong correlation between these two parameters offers deeper insights into the consistency and reliability of the stabilization process. A robust linear relationship, as determined through regression analysis, allows for accurate prediction of UCS values based on CBR measurements (and vice versa). This not only affirms the effectiveness of the stabilization method but also facilitates practical applications where one parameter can be reliably inferred from the other, thus optimizing time and resources in field and laboratory evaluations. Moreover, the importance of this relationship highlights the impact of geo-polymerization on enhancing both UCS and CBR concurrently. The ability to model this correlation with high statistical confidence evidenced by metrics such as the multiple R, R^2 , F-value, and P-values provides compelling empirical support for the success of the GP treatment.

Accordingly, the developed regression analysis examining the correlation between CBR and UCS values of GP-stabilized lithomargic soil is shown in Figure 6,

which reveals a strong linear affiliation. The high multiple R value of 0.9916 specifies an almost perfect relationship, while the R^2 value of 0.9834 displays that 98.34% of the changeability in CBR can be featured to UCS. The model's import is further accentuated by an F-value of 767.85 and a significance F of 6.00791×10^{-13} . The regression coefficient was found to be 6.2152, pointing to a sizeable positive impact of CBR on UCS. The intercept value is 81.4983, with both coefficients being exceedingly significant P-value < 0.0001. Thus, understanding this relationship is considered essential for accurately interpreting the strength improvements and their implications for the performance of stabilized soils in practical pavement engineering applications.

3.3 Prolonged Strength Development

The prolonged strength development of the GP-stabilized lithomargic soil was systematically evaluated through UCS and soaked CBR tests conducted at various systematic curing intervals from 0 to 56 days. The results are, respectively, presented in **Figures 7 and 8**.

3.3.1 Prolonged UCS Test Results

The UCS testing was carried out following the ASTM method for prolonged curing [30]. The soil specimens were stored in a desiccator containing a small amount of water to maintain a constant relative humidity, with the temperature controlled at approximately 26–29°C [15].

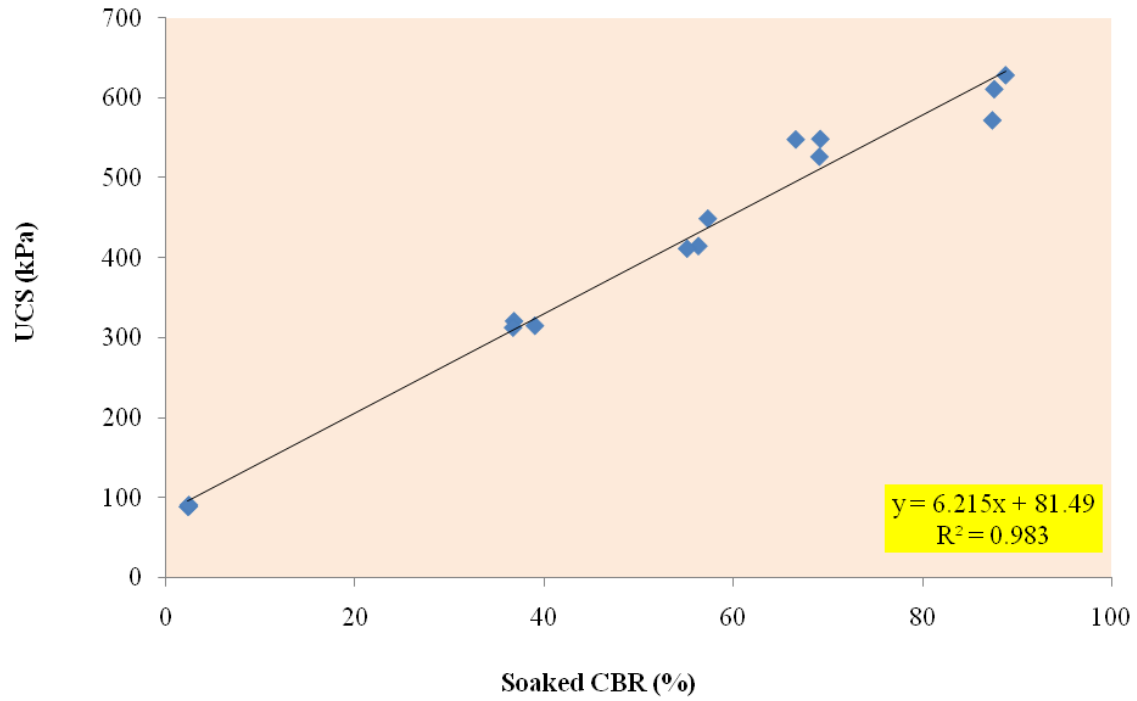


Figure 6: Relationship between UCS and CBR upon geopolymer stabilization

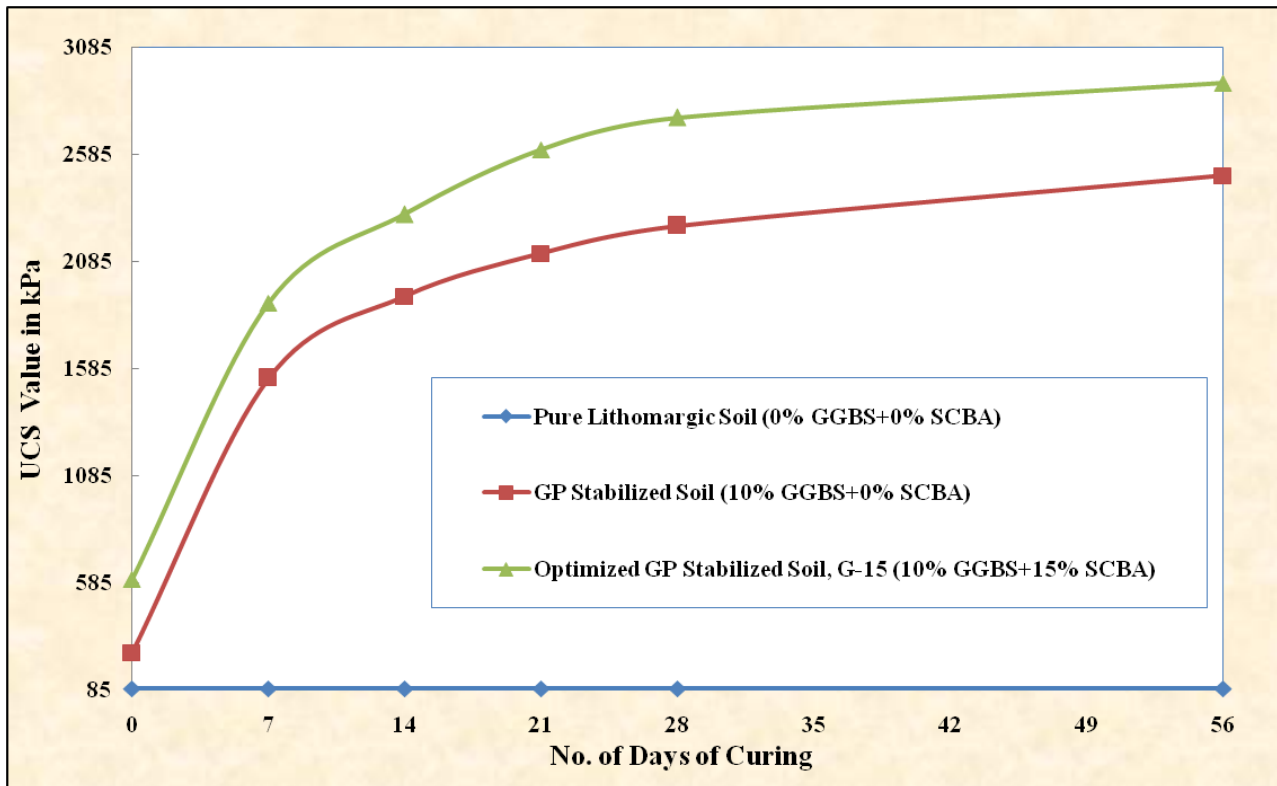


Figure 7: Prolonged UCS development for the selected GP-stabilized lithomargic soil blends.

This method ensured that the samples were cured under consistent environmental conditions, which is crucial for obtaining reliable results. The pure lithomargic soil showed no significant change in UCS over the entire curing period. This highlights the natural soil's lack of self-cementing properties, making it unsuitable for applications requiring high strength. In stark contrast, the GP-stabilized soils exhibited a marked increase in UCS over time. At 0 day, the UCS of the optimized GP-stabilized soil (10% GGBS + 15% SCBA) was 602 kPa, far exceeding the 262 kPa recorded for the GP-stabilized soil without SCBA. This early strength gain can be attributed to the rapid formation of a GP matrix, which effectively binds the soil particles.

As curing progressed, both stabilized soil samples continued to gain strength. The trend continued, with the UCS of the optimized soil reaching 3.84 times higher strength at 56 days when compared to the same at 0 day. This continuous strength gain is indicative of the ongoing GP process, where the formation of C-S-H and C-(Na)-A-S-H gels densifies the soil matrix, reducing porosity and enhancing particle cohesion. The superior performance of the optimized soil mix can be attributed to the synergistic effect of SCBA, which, when combined with GGBS, enhances the Si/Al ratio, leading to a more robust and cohesive GP network. This network not only provides higher early strength but also sustains strength development over an extended curing period.

3.3.2 Prolonged Soaked CBR Test Results

The CBR tests were similarly conducted at intervals of 4, 14, 21, 28, and 56 days to evaluate the penetration resistance capacity of the soils under soaked conditions [15]. The results, depicted in **Figure 8**, show a clear trend of increasing CBR values for the stabilized soils, in contrast to the pure lithomargic soil, which maintained a low and constant CBR value of 2.4% throughout the curing period.

For the GP-stabilized soil with 10% GGBS (0% SCBA), the CBR value increased significantly from 29.7% at 4 days to 192% at 56 days. The optimized soil mix (10% GGBS + 15% SCBA) demonstrated even more pronounced improvements, with CBR values rising from 88.7% at 4 days to 269% at 56 days. This substantial enhancement in CBR is largely due to the densification of the soil matrix, driven by the formation of a strong alumino-silicate network during the GP process. The rapid increase in CBR values, particularly during the early curing stages (4–21 days), suggests that the soil matrix achieves significant strength within a short time frame. This makes it highly

resistant to deformation under load, which is critical for pavement subgrade applications where high CBR values are essential for long-term performance. The higher CBR values observed in the optimized soil mix are attributed to the enhanced GP network formed by the inclusion of SCBA. The increased Si/Al ratio resulting from SCBA addition leads to a more stable soil structure [24], capable of withstanding higher loads and resisting water-induced weakening in long run.

3.4 Microstructure Analysis

The microstructure of the GP-stabilized lithomargic soil was thoroughly investigated using scanning electron microscopy (SEM). High-resolution images were captured by scanning the samples with a focused electron beam, providing detailed insights into crystal orientation and surface morphology at two distinct magnification levels [31]. The SEM analysis was crucial in verifying the formation of the alumino-silicate structure, which results from the reaction between GGBS and SCBA in the presence of the GP solution. This action plays a key role in binding the soil particles together while reducing voids.

Figure 9 presents SEM images of the optimized soil sample (G-15 mix) after 1 week of casting, compacted to Proctor densities, revealing a gray-colored, densely packed, flake-like structure indicative of a robust alumino-silicate matrix. This morphology is characteristic of the hydration products formed from the interaction of precursor with the GP activator solution. The polymerization process fosters the development of this dense, flake-like aluminosilicate structure, significantly reducing the porosity within the soil matrix. The GP activator solution is instrumental in the formation of this compact structure, resulting in a durable and mechanically resilient material. The SEM analysis further demonstrates that the sample exhibits a highly compact and uniform microstructure, free from significant cracks or discontinuities. This is attributed to the polymerization compounds formed through the alkali activation of the GGBS-SCBA precursors, which effectively seal pore spaces and enhance particle packing. The deposition of polymerization, that is, hydration compounds (like C-A-S-H, N-A-S-H) within the soil matrix, also greatly improves the bonding between soil particles [22]. This enhanced bonding directly contributes to the increased UCS and higher resistance to penetration, as evidenced by the CBR test results revealed earlier.

The morphological changes observed in **Figure 9** clearly illustrate the transformation of the soil's

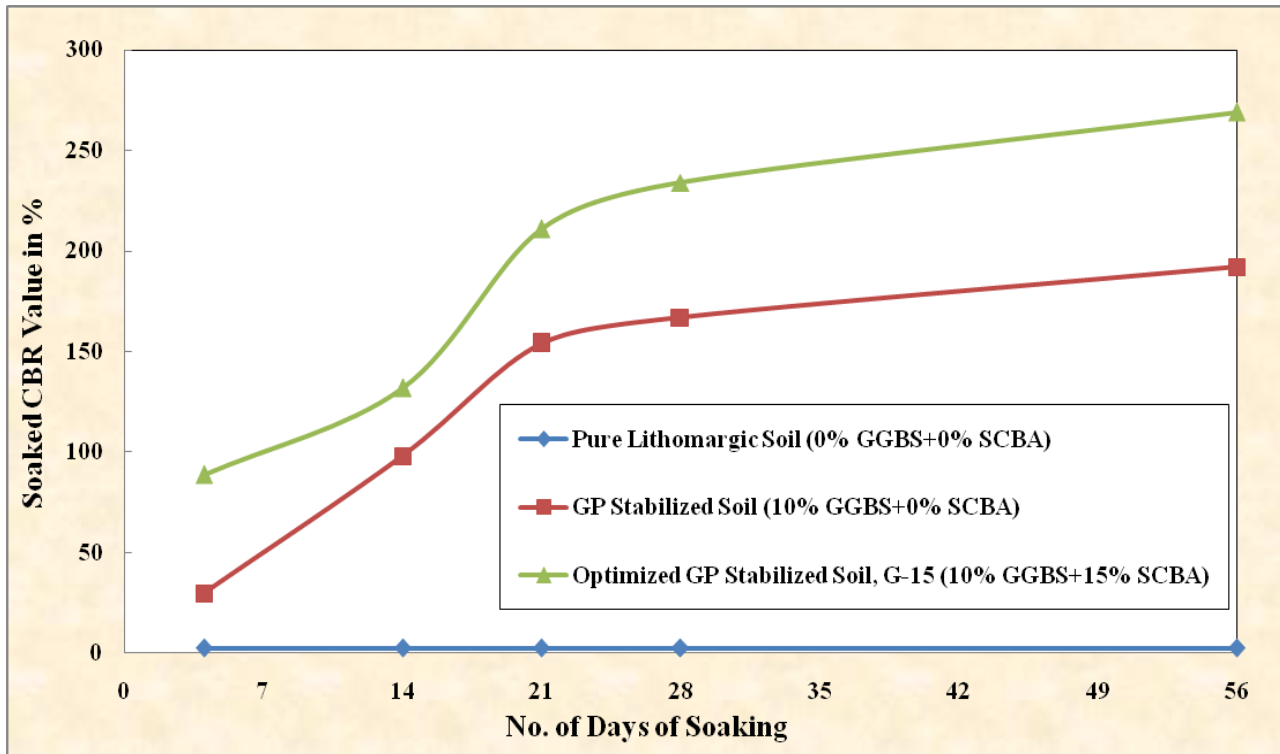
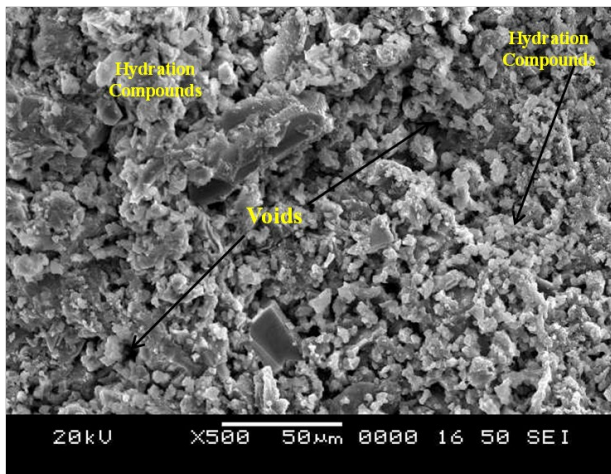
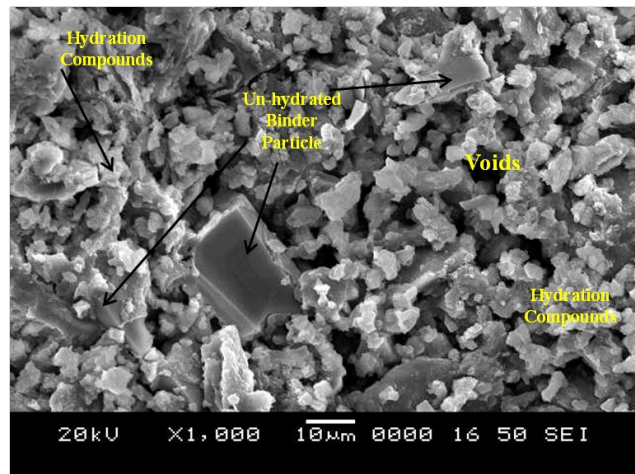


Figure 8: Prolonged CBR development for the selected GP-stabilized lithomargic soil blends.



(a) Magnification x500 and 50 micron scale



(a) Magnification x1000 and 10 micron scale

Figure 9: Scanning electron micrograph of optimal GP-stabilized shed soil matrix.

microstructure due to the formation of GP gel, which is crucial for understanding and ensuring the enhanced mechanical properties of the GP-stabilized soil. These SEM results provide a clear explanation for the observed improvements in the soil's strength and durability, offering a microscopic perspective on the macroscopic benefits achieved through GP stabilization.

3.5 Pavement Design and the Cost Analysis

For rigid pavement design applications, consistent with IRC: SP:62, the modulus of subgrade reaction (k) can be derived from the saturated CBR value (soaked) of the earth. Given the increase in the saturated CBR value of GP-modified lithomargic soil subgrades, it is possible

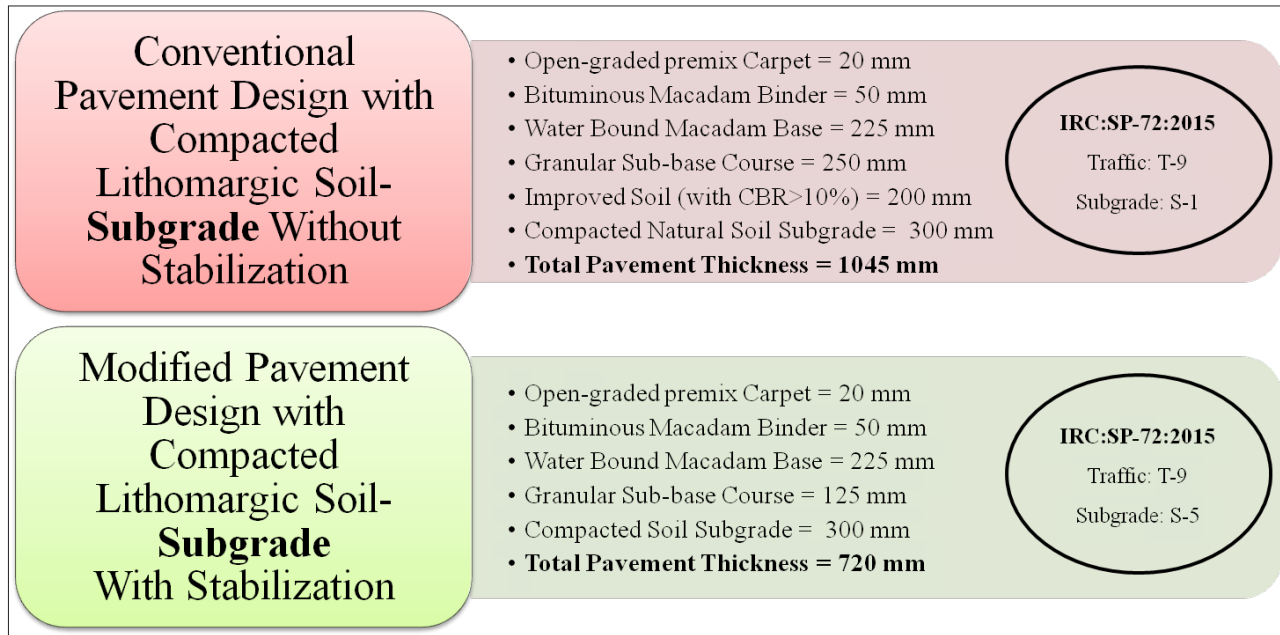


Figure 10: Typical low-volume flexible pavement design composition (IRC: SP-72).

to develop cost-effective design compositions for rigid pavements on low-volume rural roads. The k -value improved from 21 MPa/m for unmodified soil to 140 MPa/m at the optimum mix dosage, representing approximately a 567% enhancement. Similarly, for flexible pavements, following the guidelines in IRC: SP-72, a typical pavement composition for unmodified and GP-modified lithomargic soil subgrades is illustrated in **Figure 10**, designed for traffic of 1.5 million standard axles, categorized under traffic category T-9 as indicated by IRC: SP-72 [17]. From the ballpark pavement design symphony, using the optimized GP modifier, a 45% reduction in material usage was achieved for stabilized lithomargic soil when compared with that of the unstabilized soil.

Further, a comprehensive cost analysis was performed to evaluate the economic advantages of utilizing GP stabilization in pavement construction. The analysis incorporated material costs based on the 2018 rates provided by the Public Works Department of Mangalore, India, along with price estimates from bulk suppliers for the stabilizing agents used in constructing the lower layers of pavement. The cost savings were determined by comparing a conventional pavement design with a GP-modified design, as illustrated in **Figure 10**. The tentative conventional design specifies a granular subbase (GSB) thickness of 250 mm, an improved subgrade of 200 mm (with a CBR > 10%), and a compacted subgrade of 300 mm. In contrast, the GP-modified design reduces the GSB thickness to 125 mm

and entirely removes the need for the improved subgrade layer while retaining the same 300-mm thickness for the GP-modified compacted subgrade. The cost analysis for producing 1 m³ of GP-stabilized soil involved calculating the expenses associated with each material used in the stabilization process. The mix includes 10% GGBS by weight, equating to 178 kg at a unit cost of INR 3 per kg, resulting in a total cost of INR 534. Additionally, 15% SCBA by weight is used, amounting to 267 kg at INR 1 per kg, totaling INR 267. Liquid sodium silicate is required at 68.46 kg, costing INR 3 per kg, bringing the total for this component to INR 205.38. Sodium hydroxide flakes are added at 3.87 kg, with a cost of INR 13.5 per kg, totaling INR 52.29. To achieve the required water-to-binder (w/b) ratio and OMC, 211.36 kg of water is incorporated, costing INR 0.05 per kg, amounting to INR 10.57. Altogether, the total material cost for producing 1 m³ of GP-stabilized soil is INR 1069.24. In terms of pavement application, this unit cost translates into a total expenditure of INR 438.27 m² for constructing the lower layers of pavement using GP-modified soil. This offers a cost-effective alternative compared to the conventional design, which incurs a higher cost of INR 490 per m². This results in a cost saving of INR 51.73 per square meter. For a standard 1-kilometer rural road with a width of 3.75 m, the total savings amount to approximately INR 193,979. This substantial cost reduction, combined with the improved performance characteristics of GP-stabilized soil, positions it as a highly attractive option for rural road construction,

especially in regions where cost efficiency and long-term durability are critical considerations.

Hence, the implementation of GP stabilization in pavement design not only enhances the structural performance of pavements but also offers significant economic advantages. When applied to large-scale infrastructure projects, these savings can contribute to the development of more sustainable and cost-effective road networks, particularly in developing regions. However, precise design for both flexible and rigid pavements requires studying actual field conditions to develop appropriate composition designs. The results are promising, indicating substantial savings in natural or virgin materials for pavement construction and reduced construction costs, thereby promoting sustainability and economic efficiency in construction [1,10]. Additionally, this study proffers a sustainable resolution for the disposal issues associated with SCBA and blast furnace slag, which would otherwise be destined for nondegradable landfills.

4 Conclusions and Future Scope

This work underscores the considerable potential of geopolymeric cement, especially designed with GGBS and SCBA, for the stabilization of lithomargic soils. The optimal geotechnical qualities attained with a dose of 10% slag and 15% SCBA with GP solution (composed of caustic soda and water glass) have been identified as the most suitable. The elevated CBR and UCS values of the stabilized soil highlight the efficacy of GP-based treatments in enhancing subgrade effectiveness. The significant improvements in MDD, UCS, and CBR at a particular GGBS and SCBA content are the result of a synergistic interplay between optimized geopolymerization, effective aluminosilicate gel formation, and enhanced particle interactions facilitated by alkali activation verified through SEM analysis. These mechanisms contribute to the formation of a dense, cohesive, and mechanically strong soil structure, which is reflected in the superior soil engineering properties. However, exceeding the optimal precursor dosage leads to a decrease in strength, underscoring the importance of maintaining the right balance in mix design for achieving optimal soil stabilization outcomes. Additionally, the prolonged strength development was systematically evaluated through UCS and soaked CBR tests conducted at various systematic curing intervals from 0 to 56 days. Furthermore, the improved modulus of subgrade reaction (k-value) and the optimized design compositions for both rigid and flexible pavement designs

indicate that the approach can lead to more economical and sustainable pavement designs for low-volume roads.

Moreover, the consumption of industrial spin-offs such as SCBA and blast kiln slag addresses significant environmental concerns by providing a sustainable alternative to conventional disposal methods. This contributes to reducing the burden on landfills and mitigating environmental degradation. Overall, the study offers valuable insights for practicing engineers, promoting the adoption of innovative stabilization techniques that enhance subgrade performance while ensuring cost-effectiveness and sustainability in pavement construction.

Future investigations may be broadened to examine further performance characteristics, including durability assessments (such as alternative wetting-drying and freeze-thaw tests), triaxial characteristics, permeability, consolidation, rutting actions on pavement models, cyclic loading experiments, splitting tension tests, and retained endurance. Such investigations would enhance confidence in the use of GP stabilizing combinations for shedi soil subgrades. Furthermore, pavement designs informed by contemporaneous traffic data and field circumstances have to be examined to use these stabilizing strategies across low-volume and high-volume roadway contexts.

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