Indian Journal of Engineering & Materials Sciences
Vol. 32, August 2025, pp. 509-519
DOI: 10.56042/ijems.v32i04.15038

Hydrogel bonding meets pozzolanic reaction: A dual approach to soil stabilization

Aditya Kumar Anshu[a*] & Yamem Tamut[b]

[a]Department of Civil Engineering, National Institute of Technology, Arunachal Pradesh 791 113, India

[b]Department of Civil Engineering, NERIST, Arunachal Pradesh 791113, India

Received: 12 November 2024; accepted: 15 July 2025

The present paper has addressed the development of the guar gum (GG) biopolymer and fly ash (FA) in soil stabilization with the objective of improving the geotechnical properties of weak soils. Unconfined compressive strength (UCS) and california bearing ratio (CBR) tests have been used to evaluate the performance of soils with varying proportions of GG and FA during different curing periods in the laboratory. The UCS results have indicated that the maximum response has been observed with 2% GG and 5% FA, where the UCS has risen considerably from 83.15 kPa in untreated soil to 356.11 kPa after 28 days of curing. Similarly, the CBR tests conducted under unsoaked conditions have shown an increase from 6.34 in untreated soil to 12.32 with the same 2% GG and 5% FA mix. The soaked CBR values have also improved, reaching 7.67% compared to 4.72% in untreated soil. The findings have demonstrated that soil strength has been significantly enhanced with curing time, with the most notable improvements occurring within the first seven days and continuing up to 28 days as a result of pozzolanic reactions. These outcomes have suggested that the integration of GG and FA has represented a cost-effective and environmentally friendly stabilization technique, offering enhanced compressive and load-bearing capacity, particularly in problematic soil conditions, and serving as a sustainable substitute for conventional chemical stabilizers such as cement and lime.

Keywords: California bearing ratio, Fly ash, Guar gum, Unconfined compressive strength

1 Introduction

Geotechnical engineering soil stabilization is a major issue of concern that directly influences the safety, durability and functionality of infrastructure development initiatives including roads, bridges and buildings. Where the natural soil is very weak, expansive or unsuitable to be in place, stabilization is done to improve the properties of soil such as its load bearing ability, shear strength and environmental degradation. The use of chemical agents like cement and lime has in the past been largely used in soil stabilization methods. These methods have been shown to be effective but have been linked to high costs, high amounts of energy use and negative effects on the environment especially the effects on greenhouse gases. Due to the growing needs of infrastructure requirements in the world, there is also the increased requirement of more sustainable and affordable means of stabilization. Over the past few years, there has been an increase in the popularity of eco-friendly soil stabilization methods, which can be attributed to the fact that people are becoming increasingly concerned about the environmental effects of the traditional practices. Alternatives that are sustainable like using natural polymers (biopolymers) and industrial waste materials are making inroads. This paper analyzes two of these materials, guar gum, a natural biopolymer and fly ash, a coal combustion byproduct. These two materials together are a promising way of enhancing the geotechnical characteristics of the soils without causing much environmental damage. Guar gum has been researched on the strength and adhesiveness of soils because it is a good bonding agent and fly ash offers pozzolanic reactions that ensure the long-term durability of the soil and its strength. Combining the two materials may have a potential to provide a sustainable solution to large-scale soil stabilization projects.

There is no higher value to soil stabilization in geotechnical engineering. Any structure is built on solid, sound soil and in a case where the soil is weak, the structure of the building, road, and other infrastructure can have severe structural problems such as settlement, cracking and even collapse. Since the process of urbanization is accelerating and populations are growing worldwide, the need to develop infrastructure in regions characterized by

*Corresponding author: (E-mail: adityaanshu12345@gmail.com)

suboptimal soil is growing. This has, in its turn, triggered the engineers and researchers to find new ways of enhancing the soil properties in a manner that is effective and sustainable. The traditional methods of soil stabilization normally include incorporation of chemical elements such as lime or cement in the soil. An example is cement stabilization, which increases the strength of soils by causing hydration reactions resulting in cementitious bonds among particles of the soils. Lime stabilization also functions in a similar way especially in clay soils whereby it lowers plasticity and elevates workability and strength. Although these techniques are popular and suitable, they have disadvantages. Cement production is a major source of carbon dioxide emissions with about 8 % of all CO_2 emissions in the world being attributed to cement production[1]. Lime production also has significant carbon footprint and may cause environmental harm via exploitation of the natural limestone resources and release of particulate matter during the production process[2].

As the need to ensure sustainable development, as well as the increased focus on the issue of climate change, alternative methods of soil stabilization become more appealing. They can be solved by using biopolymers, including guar gum. Guar gum is a polysaccharide that is a galactomannan and extracted out of the guar seed of the plant Cyamopsis Tetragonoloba. It has been extremely applicable in food processing and pharmaceutical industries because of its thickening, emulsifying and stabilizing properties. When used in the situation of the soil stabilization, guar gum performs the role of a binder, which enhances the cohesive strength of the soil, making it more resistant to shear forces and less prone to erosion and cracks[3]. Moreover, guar gum is non-toxic, biodegradable and can be obtained sustainably; hence it is an environmentally friendly replacement of the conventional chemical stabilizers[4]. Another material that has attracted more attention in the area of soil stabilization is fly ash, which is a by-product of coal burning, in power plants. Fly ash is mainly formed with small particles of silica, alumina, and iron oxide and it contains pozzolanic qualities, that is, it can react with calcium hydroxide to form cementitious bases. This renders fly ash an excellent stabilizing compound especially in enhancing the long-term strength and durability of soils. Fly ash use in soil stabilization is not only an effective yet affordable remedy since it helps misdirect landfill waste, but also an ecologically positive practice, since it limits the use of virgin materials in constructions.

1.1 Previous studies

The performance of biopolymers in geotechnical applications, especially in the increase of soil strength and stability, has been extensively proven in previous research. As an example, biopolymers were found to highly enhance shear strength and decrease soil permeability, thus they can be used in sustainable ground improvement efforts[5,6]. They also have been demonstrated to reduce the collapsing effects of problematic soils as well as to address dispersion and dusting issues in another environment[7-11]. A broad assortment of biopolymers, such as agar, xanthan gum, guar gum, gellan gum, modified starch, and beta-glucan have been investigated with findings confirming their potential to improve the engineering behavior of a wide range of soil types, including clay, sand, and silt[12-15]. Specifically, guar gum and xanthan gum were identified as extremely efficient stabilizers, and various studies indicated that their inclusion could enhance greatly the compressibility of soils, shear strength, and their durability[16-17].

According to Rehman and Jafri[18], the addition of guar gum biopolymer to low- as well as high-plasticity (CL) and high-plasticity (CH) clays improved their mechanical behavior significantly with 182.64% and 243.30% unconfined compressive strength, respectively, at 2% guar gum biopolymer content after curing. The results demonstrate guar gum as a potential and viable substitute to enhance the strength of various types of clay. On the same note, Mohan and Adarsh[19] noted that the compaction properties and california bearing ratio (CBR) strength of low-strength Kuttanad clay were significantly enhanced when it was stabilized with guar gum. Significant strength improvements were also obtained after 28 days of drying, showing the efficiency of this biopolymer as eco-friendly stabilizer. When guar gum is used together with other biopolymers and industrial by-products, the performance of the guar gum will be further increased. In particular, Puneeth *et al.*[20] proved that the addition of bagasse ash along with guar gum and xanthan gum enhanced the stability and the strength of red soil. The effectiveness of such combinations is not just to enhance stabilization practices of soils but also through the beneficial reuse of industrial waste equipment that can be used in a sustainable way.

In recent times, geotechnical research has focused on the behavior of biopolymers on soil behavior by adding them into soil mixtures in specific ratios to form new materials with unique properties and improved performance in different engineering activities[21]. Organic polymers (biopolymers) obtained by a range of biological organisms have become a subject of particular interest as a sustainable, alternative source of stabilizers compared to traditional ones[4]. As carbon-neutral materials, biopolymers are always considered renewable because they are made out of non-food agricultural crops that are always very abundant. As a result, the introduction of biopolymers in geotechnical engineering is considered the way toward a much more sustainable and environmentally-conscious sector[5].

Besides the mechanical strength, guar gum influence the hydro-mechanical behavior of soils as well. Anandha *et al.*[22] emphasized the benefits of guar gum in lowering the permeability and increasing the strength of the soil particularly in sand-clay blends. The polysaccharide amendment also enhanced the adsorption capacity of heavy metals and was therefore applicable in the environmental sensitive applications. Guar gum has also been used in other studies with synthetic fibers such as polyurethane acrylates. Oprea and Oprea[23] investigated the biodegradation of crosslinked polyurethane acrylates in combination with the guar gum in natural soil conditions. Although the degradation rate got larger, the mechanical properties of the composites got lower, which implied that the lifespan and behavior of the composites in soil stabilization could be influenced by the use of guar gum on synthetic polymers.

Fly ash-stabilized soils are also used with polymers and geosynthetics which enhance their performances. Karami *et al.*[24] (2021) examined the effects of secondary additives, including polymers and lime and established that the soil, flyash, lime, enzyme combination had a greater bearing capacity. This ideal mixture is both beneficial in stabilization of soft subgrades and also reduces the amount of waste that fly ash generates. Other research has proved that it is effective to enhance physical and mechanical properties of soil such as California Bearing Ratio (CBR), shear strength, and compaction properties. Indicatively, a study conducted by Munda *et al.*[25] revealed a significant increase in the unconfined compression strength (UCS) and CBR value of expansive soils with the addition of 20 percent fly ash and 1.5 percent nanoSiO_2, which is a good foundation in civil infrastructure undertakings. Another method is the addition of lime or enzyme to fly ash-stabilized soils. Renjith *et al.*[26] maximized fly ash-based soil stabilization by incorporating lime and enzymes whereby 1% of 1:500 diluted enzyme, in combination with 2% lime, was found to improve the load bearing capacity of the soil greatly. This approach helps in sustainable utilization of fly ash, which also provides an alternative of stabilizing pavements as well as waste reduction. Both fly ash and guar gum, either used alone or in combination with additives, provide significant improvements in soil stabilization. Fly ash is ideal for large-scale infrastructure projects, while guar gum offers an eco-friendly, biodegradable solution for more environmentally sensitive applications. Together, they contribute to the advancement of sustainable construction and infrastructure development.

2 Materials and Methods

This section outlines the materials used in the study, which includes the soil sample, guar gum, and fly ash, along with the methodologies employed to assess their impact on the geotechnical properties of the soil. The laboratory tests conducted in this study include grain size distribution, Atterberg limits, specific gravity, standard proctor test, unconfined compression test (UCS), and California Bearing Ratio (CBR) test.

2.1 Material

The soil used in this study was collected from a landslide-prone area in Hoj village, located in Toru Circle of Papum-pare district, Arunachal Pradesh, India. The geotechnical properties of the soil, such as its index properties and compaction characteristics, were determined in the laboratory. The soil sample was classified as poorly graded sand (SP) according to IS soil classification. Table 1 presents the compaction and index properties of the soil. Figure 1 shows the site location where sample are collected. Figures 2 and 3, illustrate the grain size distribution curve of soil sample and Optimum moisture content vs maximum dry density of the untreated soil sample.

Table 1 — Compaction and index properties of soil.

Property	Value
Water Content (%)	2.98
Liquid Limit (LL) (%)	22.8
Plastic Limit (PL) (%)	NP
Specific Gravity (G_s)	2.69
Gravel size (>4.75mm) (%)	5.50
Sand size (0.075-4.75mm) (%)	92.30
Silt size (0.002-0.075mm) (%)	2.20
Clay size (<0.002mm) (%)	0.00
Coefficient of Uniformity (C_u)	2.36
Coefficient of Curvature (C_c)	1.367
Maximum Dry Density (KN/m³)	1.783
Optimum Moisture Content (%)	11.48

Fig. 1 — (a) Site location of collected soil sample and (b) Sieved soil sample.

Fly ash is a fine powder that is a byproduct of burning pulverized coal in thermal power plants. It consists primarily of silica, alumina, and iron oxides and is captured from exhaust gases using electrostatic precipitators or bag filters. This byproduct is widely used in the construction industry, particularly in concrete production, because of its beneficial properties. Class C fly ash is generally considered more suitable for soil stabilization. This is because Class C fly ash contains a higher percentage of calcium oxide (CaO), or lime, which gives it self-cementing properties. When mixed with soil, Class C fly ash reacts with water and forms cementitious compounds that improve the strength, durability, and stability of the soil. This makes it particularly effective for stabilizing a wide range of soils, especially those with high plasticity or poor load-bearing capacity. Fly ash will be collected from the Brick Oliteprivate ltd., Guwahati for the purpose of the research work as shown in Fig. 4a. Guar gum is a galactomannan polysaccharide extracted from guar beans that has thickening and stabilizing property as shown in Fig. 4b. Guar gum used for the study was purchased from Purix global company, Indore. Guar

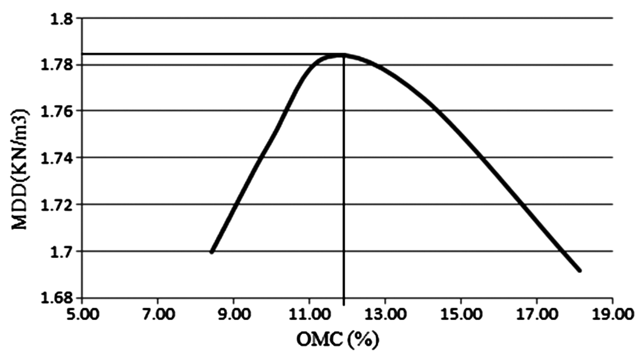

Fig. 3 — OMC and MDD of untreated soil.

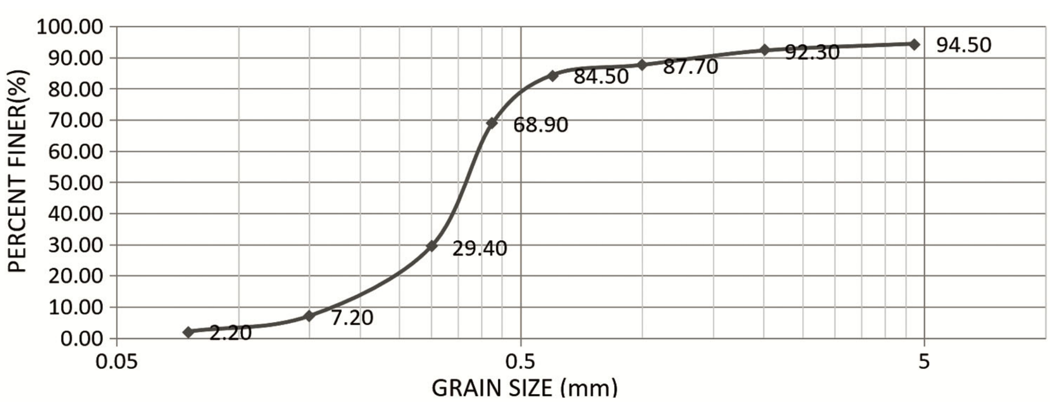

Fig. 2 — Grain size distribution curve of soil sample.

gum (GG) is a natural, biodegradable, vegetable polymer that is mostly derived out of the seeds of Cyamopsis tetragonoloba, also called guar beans. It consists of polysaccharides, chiefly galactose and mannose, and may be in a cationic form or in an anionic form based on how it is chemically processed[27].

GG is a gelling, thickening, suspending and flocculating agent extracted out of the guar bean splits and utilized in various industrial applications such as the oil recovery sector, cosmetics sector, paper sector, textile sector, paints sector, pharmaceutical sector, as well as food industry[27,28]. It is also unique in its high-volume production that surpasses one million tonnes per year hence it is commercially available and can be bought at a low cost hence making it one of the most accessible natural polymers in engineering uses[29]. Guar gum is chemically regarded as one of the most water-soluble polysaccharides, and the number of hydroxyl groups in its structure makes it easier to form hydrogel networks with the soil particles and ions, which has facilitated the formation of hydrogel networks in the soil structure[27,30] as shown in Fig. 5. This bonding process has been demonstrated to enhance important geotechnical characteristics such as unconfined compressive strength, shear strength and hydraulic conductivity, which has made GG a prospective eco-friendly stabilizer[31].

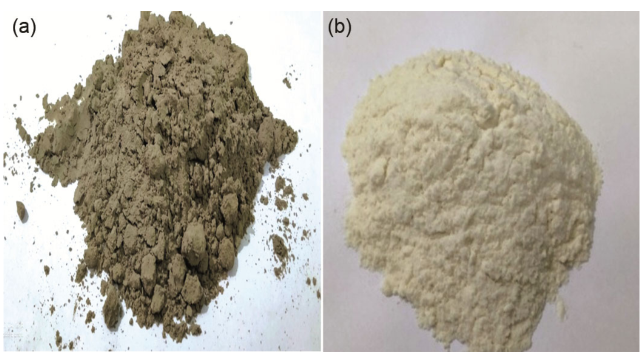

Fig. 4 — Effect of stabilizers on soil properties (a) Guar gum and (b) Fly ash.

In the present study on the properties of soil was conducted UCS tests on soil were done curing the samples for 0,3,7 and 28 days. UCS tests on soil were done for different percentages of Guar gum (0.5%, 1%, 1.5%, and 2%) and fly ash (5% and 10%). CBR tests also performed out on natural or compacted soils in different percentages of Guar gum (0.5%,1%,1.5%, and 2%) and fly ash (5% and 10%) in water soaked or un-soaked conditions and the results so obtained are compared with the curves of standard test.

3 Results and Discussion

This section presents the results of stabilization of soil with Guar gum and fly ash. To determine the optimum moisture content (OMC) and maximum dry density (MDD) of soil and treated soil samples. The increase in strength condition was established by conducting unconfined compression test on samples at 0-, 3-, 7- and 28-days curing, CBR tests are performed out of soil and treated soil samples in water soaked or un-soaked conditions and the results so obtained are compared with the curves of standard test. Table 2 shows details of the soil and soil mixed with different percentage of additives, Guar gum (0.5%, 1%, 1.5%, 2%and 2.5%) and fly ash (5% and 10%).

3.1 Influence of standard proctor test

The compaction characteristics of the soil samples were evaluated using the standard proctor test. The

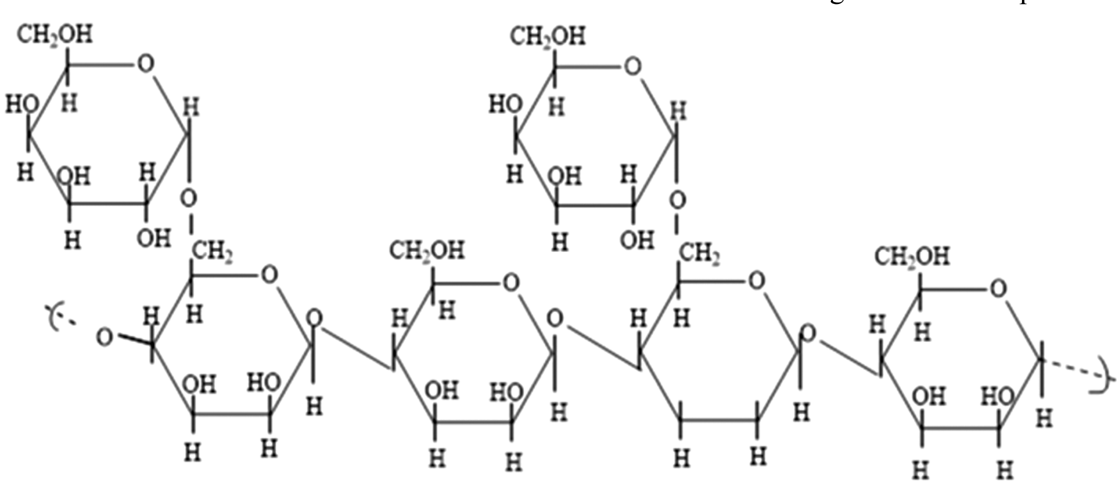

Fig. 5 — Molecular structure of guar gum (Chudzikowski 1971).

Table 2 — Details of the mixed soil specimens.

S.NO.	Name of the mix	Particulars of the mix
1	Soil+ GG (0.5%) + FA (5%)	Soil+ 0.5% Guar gum by weight of total solids+5% fly ash by weight of total solids
2	Soil + GG (1.0%) + FA (5%)	Soil+ 1.0% Guar gum by weight of total solids+5% fly ash by weight of total solids
3	Soil + GG (1.5%) + FA (5%)	Soil+ 1.5% Guar gum by weight of total solids+5% fly ash by weight of total solids
4	Soil + GG (2.0%) + FA (5%)	Soil+ 2.0% Guar gum by weight of total solids+5% fly ash by weight of total solids
5	Soil + GG (2.5%) + FA (5%)	Soil+ 2.5% Guar gum by weight of total solids+5% fly ash by weight of total solids
6	Soil +GG (0.5%) +FA (10%)	Soil+ 0.5% Guar gum by weight of total solids+10% fly ash by weight of total solids
7	Soil + GG (1.0%) + FA (10%)	Soil+ 1.0% Guar gum by weight of total solids+10% fly ash by weight of total solids
8	Soil + GG (1.5%) + FA (10%)	Soil+ 1.5% Guar gum by weight of total solids+10% fly ash by weight of total solids
9	Soil + GG (2.0%) + FA (10%)	Soil+ 2.0% Guar gum by weight of total solids+10% fly ash by weight of total solids

Table 3 — Influence of admixtures on OMC and MDD for guar gum and fly ash (5%).

Sample Name	OMC (%)	MDD(g/cc)
Untreated Soil	11.48	1.783
Soil+ GG (0.5%) + FA (5%)	12.69	1.718
Soil + GG (1.0%) + FA (5%)	13.18	1.698
Soil + GG (1.5%) + FA (5%)	14.52	1.640
Soil + GG (2.0%) + FA (5%)	15.40	1.586
Soil + GG (2.5%) + FA (5%)	14.76	1.613

Table 4 — Influence of admixtures on OMC and MDD for guar gum and fly ash (10%).

Sample Name	OMC (%)	MDD(g/cc)
Untreated Soil	11.48	1.783
Soil+ GG (0.5%) + FA (10%)	15.28	1.658
Soil + GG (1.0%) + FA (10%)	13.81	1.665
Soil + GG (1.5%) + FA (10%)	12.60	1.626
Soil + GG (2.0%) + FA (10%)	10.96	1.540

results indicate that as the percentage of guar gum and fly ash increases, the maximum dry density (MDD) decreases, while the optimum moisture content (OMC) increases. For untreated soil, the MDD was 1.783 g/cm³, and the OMC was 11.48% as shown in Table 3. When the soil was treated with 2% GG + 5% FA, the MDD reduced to 1.586 g/cm³, and the OMC increased to 15.40%. This trend is attributed to the water absorption capacity of guar gum, which leads to an increase in the OMC as more water is required to achieve compaction. A similar effect was observed with fly ash, which tends to retain water, further increasing the OMC. The reduction in MDD and the corresponding increase in OMC are consistent with the expected behavior of biopolymer-stabilized soils.

The higher water retention and binding properties of guar gum lead to increased moisture requirements during compaction, which accounts for the observed trends. The addition of fly ash further enhances this effect, as its pozzolanic reaction in the presence of moisture contributes to the development of cementitious compounds, leading to improved soil structure but lower dry density. Similarly Table 4, showing the value of optimum moisture content (OMC) and maximum dry density (MDD) of the compacted samples of soil and also soil replaced with guar gum (0.5%,1%,1.5%,2%) and fly ash(10%).

3.2 Influence of unconfined compression test

The UCS test was performed to evaluate the strength of the soil samples treated with varying percentages of guar gum and fly ash. The samples were tested at 0, 3, 7, and 28 days of curing to assess the impact of curing timeon soil strength. The results indicate a significant improvement in UCS with the addition of both guar gum and fly ash, particularly with longer curing periods from Fig. 6 (a-d). The UCS values for soil treated with 0.5% GG and 5% FA were evaluated at different curing times. The untreated soil exhibited a UCS value of 83.15 kPa at 0 days. After the addition of 0.5% GG and 5% FA, the UCS at 0 days increased to 97.88 kPa. With a curing period of 3 days, the UCS value increased to 143.85 kPa, indicating the onset of stabilization effects. The UCS further increased to 200.24 kPa after 7 days and reached 248.29 kPa after 28 days of curing. For soil samples treated with 1.0% GG and 5% FA, the UCS value at 0 days was 132.57 kPa, showing a significant increase compared to untreated soil. After 3 days of curing, the UCS increased to 165.51 kPa, and after 7 days, it rise to 225.13 kPa. By the end of the 28-day curing period, the UCS value reached 266.66 kPa, demonstrating a substantial improvement in strength over time due to the combined effects of Guar Gum and Fly Ash. For soil treated with 1.5% GG and 5% FA, the UCS at 0 days was recorded as 141.41 kPa. This value increased steadily with curing, reaching 171.68 kPa at 3 days, 230.44 kPa at 7 days, and 314.18 kPa after 28 days. The strength improvement is attributed to the interaction between GG and FA, where GG provides immediate binding effects, and FA contributes to long-term strength through

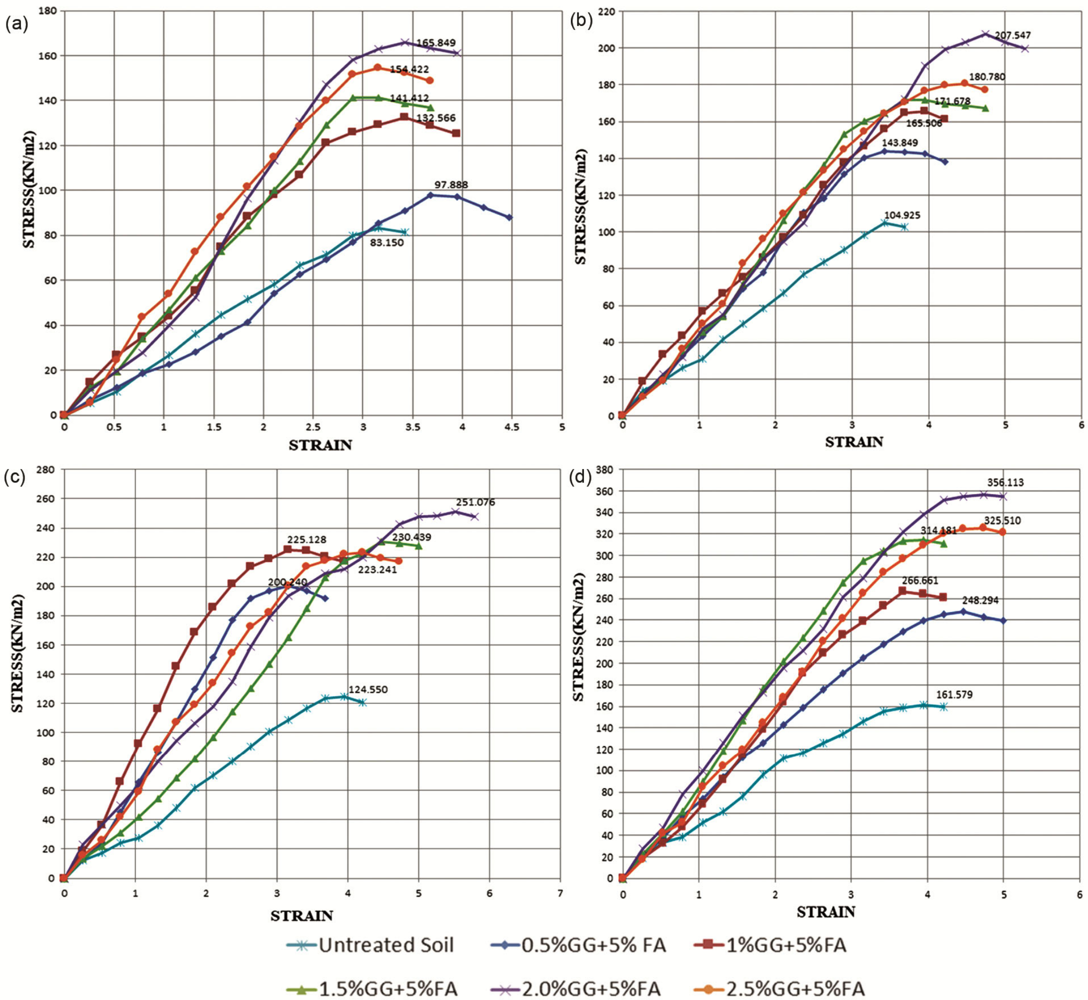

Fig. 6 — Influence of Gaur gum (0.5% to 2.5%) and fly ash (5%) on Unconfined compressive Strength of soil (a) Uncured (0 days), (b) 3 days, (c) 7 days and (d) 28 days.

pozzolanic reactions. The proportion of 2.0% GG and 5% FA yielded the highest UCS values among all the tested samples. At 0 days of curing, the UCS value was 165.85 kPa. After 3 days, the UCS increased significantly to 207.55 kPa. The UCS reached 251.08 kPa after 7 days of curing and finally achieved a value of 356.11 kPa after 28 days of curing, indicating optimal stabilization effects at this concentration of GG and FA. At 2.5% GG and 5% FA, the UCS value at 0 days was slightly lower than the 2.0% GG treatment, with a value of 154.42 kPa. The UCS increased to 180.78 kPa after 3 days of curing and reached 223.24 kPa after 7 days. After 28 days, the UCS value was 325.51 kPa. While the UCS value after 28 days was high, it was observed that increasing the GG concentration beyond 2.0% did not yield a significant improvement in strength and may even have caused a slight decrease due to the excessive water absorption properties of GG, which could lead to swelling.

As seen in the above results, curing time has a significant effect on the UCS values. The strength improvement is rapid during the first 7 days of curing, primarily due to the hydration of fly ash and the immediate binding effects of guar gum. Beyond 7 days, the strength continues to increase but at a slower rate, as the pozzolanic reactions in fly ash develop fully over time, contributing to long-term strength gain. The curing process allows the soil particles to bond more effectively, enhancing the overall stiffness and load-bearing capacity of the soil.

In addition to the tests conducted with 5% fly ash (FA), the unconfined compression test (UCS) was also performed for soil samples treated with 10% fly ash in combination with varying percentages of guar gum (GG) (0.5%, 1.0%, 1.5%, and 2.0%) at different curing times (0 days, 3 days, 7 days, and 28 days) as shown in Fig. 7(a-d). This was done to assess whether increasing the fly ash content further improves the soil's strength characteristics. At 0.5% GG and 10% FA, the UCS value for untreated soil was 83.15 kPa. The UCS increased to 102.18 kPa at 0 days with the addition of 0.5% GG and 10% FA. After 3 days of curing, the UCS improved to 146.74 kPa. Further curing led to an increase to 206.99 kPa at 7 days, and the UCS reached 273.41 kPa after 28 days of curing. This represents a steady and significant improvement in the strength of the soil over time. For the soil samples treated with 1.0% GG and 10% FA, the UCS value at 0 days was 112.77 kPa, higher than the 0.5% GG treatment. After 3 days of curing, the UCS increased to 152.85 kPa, and by 7 days, it further improved to 232.11 kPa. After 28 days, the UCS reached 308.57 kPa. This combination of 1.0% GG and 10% FA showed a significant improvement in strength, especially at longer curing times, indicating the beneficial effects of higher fly ash content. The UCS value at 0 days was 98.47 kPa, a little lower value than the one at 1.0% GG and 10% FA combination, at 1.5% GG and 10% FA. Nevertheless, the UCS rose to 181.71 kPa after 3 days of curing have followed. Curiously enough, the UCS decreased slightly after 7 days of curing to 135.39 kPa, then rose again to a level of 196.98 kPa after 28 days. The reduction of UCS at 7 days would be attributed to poor curing or excessive dependence on the fly ash content that might have caused the cementitious bonds of the soil particles to be weak. This finding indicates that 1.5 percent GG containing 10 percent FA possibly is not the most ideal mixture of soil strength-enhancing over time. In the case of soil to which 2.0 percent of GG and 10 percent of FA were

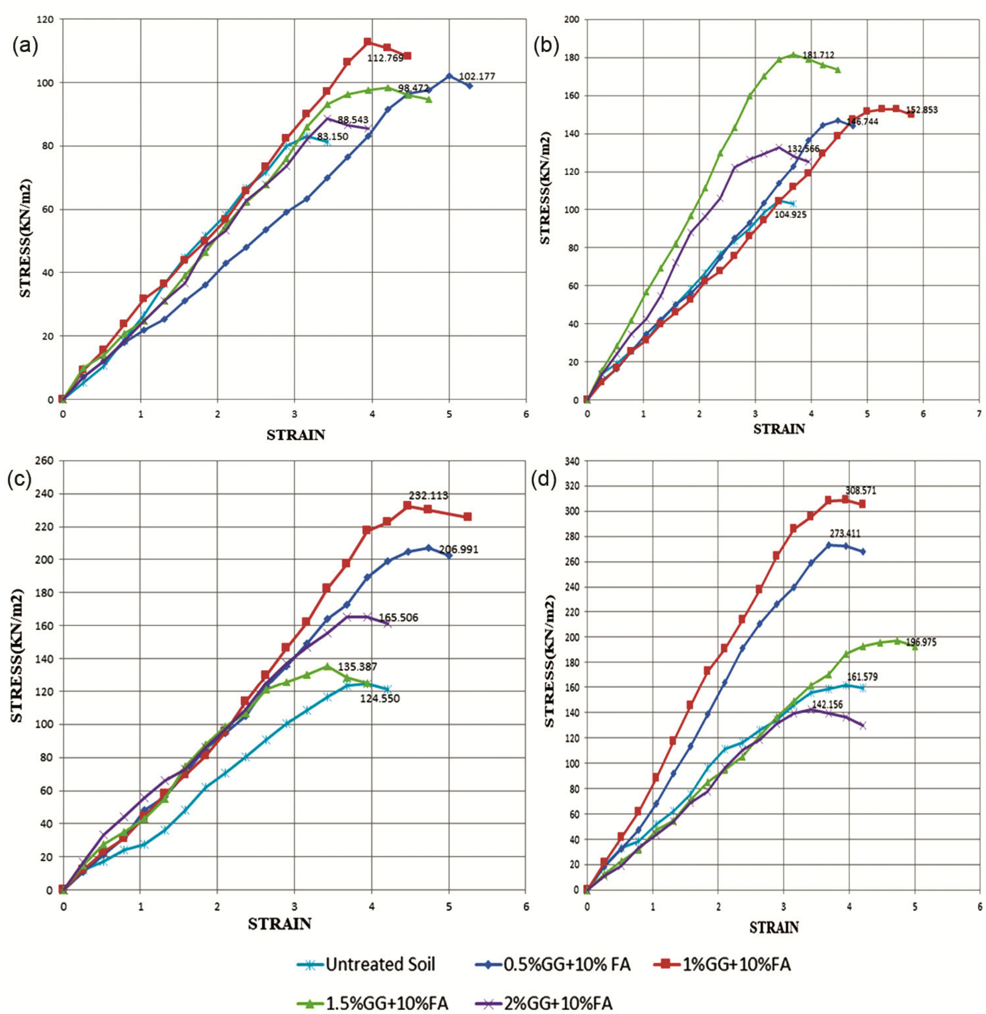

Fig. 7 — Influence of gaur gum (0.5% to 2.5%) and fly ash (10%) on unconfined compressive strength of soil (a) Uncured (0 days), (b) 3 days, (c) 7 days and (d) 28 days.

added, the value of UCS at day 0 was 88.54 kPa. The UCS level rose to 132.57 kPa after 3 days of curing which is a slight improvement as compared to other combinations. At 7 days, the UCS reached 165.51 kPa, but by 28 days, the UCS value dropped to 142.16 kPa. This decrease in strength after prolonged curing suggests that, similar to the 1.5% GG and 10% FA combination, the high fly ash content (10%) may have interfered with the soil's overall stabilization process when used with 2.0% GG.

The UCS test results for 10% fly ash demonstrate that higher fly ash content can improve the initial strength of the soil when combined with guar gum. However, in certain cases, prolonged curing times (especially beyond 7 days) resulted in reduced UCS values for specific proportions, particularly in the 1.5% and 2.0% GG combinations. This could be due to excessive fly ash leading to the formation of brittle cementitious bonds, which, while initially strong, might weaken over time due to micro-cracking or poor bonding with the soil particles. The result suggests that while 10% fly ash can offer significant strength improvements in the short term, its effectiveness may plateau or even decrease after a certain curing period when used in excess. The proportion of 1.0% GG 10% FA seems to be the best ratio to keep strength longer with the highest UCS values at 28 days (308.57 kPa).

3.3 Influence of CBR test

California bearing ratio (CBR) test is a critical assessment technique to ascertain the strength of subgrade soil and its aptness in use in construction of road and pavements. The objective of this study was to determine the effects of guar gum (GG) and fly ash (FA) on the strength of soil using the CBR test on untreated, and treated samples of soil containing various ratios of these ingredients. Soaked condition and unsoaked condition were also investigated so that performance of the stabilized soil under different moisture conditions could be tested as shown in Fig. 8. Table 5 illustrates the change in CBR of samples containing varying proportions of guar gum (0.5 % to 2.5 %) and fly ash (5 %) with no moisture (unsoaked) and with moisture (soaked).

For soil treated with 0.5% GG and 5% FA, the CBR values improved significantly compared to untreated soil. In the unsoaked condition, untreated soil exhibited a CBR value of 6.34%, while the soil

Fig. 8 — (a) Unsoaked CBR values of untreated and treated soil and (b) Soaked CBR values of untreated and treated soil.

Table 5 — CBR values of soil treatments with guar gum (0.5% to 2.5%) and fly ash (5%).

Sl. no	Sample	California bearing ratio (CBR), %	
		Un-soaked	Soaked
1.	Untreated Soil	6.34	4.72
2.	Soil+ GG (0.5%) + FA (5%)	7.82	5.16
3.	Soil + GG (1.0%) + FA (5%)	8.48	5.75
4.	Soil + GG (1.5%) + FA (5%)	10.40	6.49
5.	Soil + GG (2.0%) + FA (5%)	12.32	7.67
6.	Soil + GG (2.5%) + FA (5%)	9.73	5.46

treated with 0.5% GG + 5% FA showed a CBR value of 7.82%. In a similar manner, the CBR of untreated soil in soaked condition was 4.72 per cent and with stabilization of the soil with 0.5 % GG and 5 % FA, it was 5.16 %. This signifies moderate enhancement in the load bearing capacity of the soil. CBR values also rose at 1.0% GG and 5% FA. The unsoaked CBR value was 8.48 % and the soaked CBR value was 5.75 %. These findings indicate a significant enhancement over untreated soil, and this ratio would be more efficient in enhancing the strength of the subgrade in wet and dry environments. At 1.5% GG and 5% FA, the CBR values were 10.40% and 6.49% under unsoaked and soaked conditions respectively. This is a significant increment in the soil load bearing capacity, especially in unsoaked soils. This proportion is actually increasing with strength, indicating that even the higher concentrations of guar gum (as high as 1.5%) are exerting a stabilizing effect, at least during dry conditions. The mixture of 2.0% GG and 5% FA had the best CBR values of all the proportions that were tested. The unsoaked CBR value rose to 12.32 %, the soaked CBR value rose to 7.67 %. These findings indicate that the performance of the soil has greatly improved in dry and wet conditions. The large values of CBR demonstrates that this mixture of GG and FA is the most efficient to increase the load-bearing capacity of the soil. At 2.5% GG and 5% FA, the CBR values in the unsoaked condition were slightly lower than the 2.0% GG combination, with a value of 9.73%. In the soaked condition, the CBR value was 5.46%. Although this proportion still shows an improvement over untreated soil, the slight reduction in CBR values compared to the 2.0% GG combination suggests that increasing the GG concentration beyond 2.0% does not yield further benefits in terms of soil strength and may even lead to diminishing returns due to the excessive water absorption properties of GG.

Table 6 represents the variation in CBR values for different proportions of guar gum (0.5% to 2.0%) and fly ash (10%) under unsoaked and soaked condition. For the first sample, when 10% FA was used along with 0.5% GG, the CBR value in the unsoaked condition was 7.25%, while the soaked CBR value increased to 5.36%. The results indicate that the higher fly ash content provided some improvement in the soil's load-bearing capacity, but not as significant as the 5% FA combinations. The CBR values for the soil stabilized with 1.0% GG and 10% FA were 8.84% in the unsoaked condition and 6.12% in the soaked condition. These results indicate that increasing the fly ash content slightly improves the CBR values, especially in the soaked condition, compared to the 5% FA combinations.

Table 6 — CBR values of soil treatments with Guar gum (0.5% to 2.5%) and fly ash (10%).

Sl. no	Sample	California bearing ratio (CBR), %	
		Un-soaked	Soaked
1.	Untreated Soil	6.34	4.72
2.	Soil+ GG (0.5%) + FA (10%)	9.07	5.60
3.	Soil + GG (1.0%) + FA (10%)	11.28	6.56
4.	Soil + GG (1.5%) + FA (10%)	10.69	5.46
5.	Soil + GG (2.0%) + FA (10%)	8.55	5.09

At 1.5% GG and 10% FA, the CBR values in the unsoaked condition were 9.90%, while the soaked CBR value was 6.42%. These values show that the combination of higher fly ash content with 1.5% GG yields similar results to the 5% FA combinations, with a slight improvement in soaked conditions, but no significant change in the unsoaked condition. The combination of 2.0% GG and 10% FA yielded a CBR value of 10.80% in the unsoaked condition and 6.86% in the soaked condition. Although this proportion gives a good value of CBR it is not better than the performance of 2.0% GG containing 5% FA. This implies that adding fly ash content above 5 % does not increase the strength in proportional amounts and in some instances may result in over-stabilization whereby extreme stiffening of the soil is developed, such that minor deformations under load are not accommodated by the soil.

The CBR tests demonstrate that the mixture of fly ash and guar gum remarkably enhances the load bearing capacity of soil both in the soaked and unsoaked state. The maximum CBR was found to be 2.0% GG and 5% FA, the unsoaked CBR was 12.32% and soaked CBR was 7.67%. The fly ash content of 10 % offers a slight improvement under the soaked conditions, but is not much better than the 5 % FA blends. This implies that the best combination of GG 2.0 % and FA 5 % is the one that enhances the strength of soil especially in road and pavement construction where both dry and wet conditions are likely to be experienced.

4 Conclusion

The paper has shown the usefulness of guar gum (GG) and fly ash (FA) in improving soil when used as sustainable stabilizers. The interactions that occurred between these materials resulted in significant improvement of the geotechnical properties of the soil especially the compressive strength and load bearing capacity. A significant observation was a decline of the maximum dry density (MDD) with increase in per cent of GG and a rise in optimum moisture content (OMC). To give an example, the untreated soil had a MDD of 1.783 g/cm 3 and OMC of 11.48% and 5% FA had reduced MDD of 1.586 g/cm 3 and an increase in OMC to 15.40%. This was due to the fact that GG and FA have water adsorbing characteristics that need more water to be compressed effectively.

Besides, the unconfined compressive strength (UCS) of the soil increased greatly with the incorporation of GG and FA, especially when the soil was left to cure over a long period. As an illustration, the soil to which 1.5% of GG and 5% of FA were applied increased its UCS to 314.18 kPa after 28 days of curing as compared to 141.41 kPa at 0 days. Likewise, the results of the california bearing ratio (CBR) test revealed significant differences in case of both soaked and unsoaked condition. It was identified that the best combination was 2 % of GG, and 5 % of FA which produced the best CBR values of 12.32 % in unsoaked and 7.67 % in soaked conditions. Overall, the integration of GG and FA in soil stabilization proved to be an effective and environmentally friendly approach, enhancing soil strength and durability while offering a sustainable alternative to traditional chemical stabilizers.

Conflict of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical Approval: This article does not contain any studies with human participants or animals performed by any of the authors.

Funding: The authors did not receive financial support from any organization for the submitted work.

References

1 Lehne J & Preston F, *Making concrete change: Innovation in low-carbon cement and concrete*, (Chatham House, London), 2018.

2 Pacheco-Torgal F, Cabeza L F, Labrincha J & De Magalhaes A G, *Eco-efficient construction and building materials: Life cycle assessment (LCA), eco-labelling and case studies* (Woodhead Publishing, Cambridge), ISBN: 9780857097675, 2014.

3 Ayeldeen M, Negm A, El-Sawwaf M & Kitazume M, *J Rock Mech Geotech Eng*, 9 (2017) 329.

4 Chang I, Im J & Cho G C, *Sustainability*, 8 (2016) 251.

5 Bouazza A, Gates W P & Ranjith P G, *Geotechnique*, 59 (2009) 71.

6 Umar M, Kassim K A & Chiet K T P, *J Rock Mech Geotech Eng*, 8 (2016) 767.

7 Ayeldeen M K, Negm A M & El Sawwaf M A, *Arab J Geosci*, 9 (2016) 371.

8 Muguda S, Booth S J, Hughes P N, Augarde C E, Perlot C, Bruno A W & Gallipoli D, *Geotech Lett*, 7 (2017) 309.

9 Achal V, Mukerjee A & Reddy M S, *Constr Build Mater*, 48 (2013) 1.

10 Alam S, Das B K & Das S K, *J Hazard Toxic Radioact Waste*, 22 (2018) 04018025.

11 Chen R, Lee I & Zhang L, *J Geotech Geoenviron Eng*, 141 (2015) 04014100.

12 Chang I, Im J, Prasidhi A K & Cho G C, *Constr Build Mater*, 74 (2015a) 65.

13 Chang I, Im J, Prasidhi A K & Cho G C, *Constr Build Mater*, 77 (2015b) 430.

14 Chang I, Im J, Prasidhi A K & Cho G C, *Geoderma*, 253–254 (2015c) 39.

15 Swain K, Mahamaya M, Alam S & Das S K, in *Sustainable Civil Infrastructures: Innovative Infrastructure Geo-technology* (Springer, Cham), 2017, p. 132.

16 Latifi N, Horpibulsuk S, Meehan C L, Abd Majid M Z & Rashid A S A, *Environ Earth Sci*, 75 (2016) 1.

17 Wiszniewski M, Skutnik Z, Biliniak M & Cabalar A F, *Ann Warsaw Univ Life Sci-SGGW Land Reclam*, 49 (2017) 201.

18 Rehman M A & Jafri T, *J Appl Res Ind Eng*, 7 (2020) 329.

19 Mohan R P &Adarsh P, in *Ground Improvement and Reinforced Soil Structures: Proc Indian Geotechnical Conference 2020, Vol. 2* (Springer, Singapore), 2022, p. 423.

20 Puneeth R, Shruthi H G, Gowtham Prasad M E & Shashi Kiran C, *Turk J PhysiotherRehabil*, 44 (2023) 1162.

21 Joga J R &Varaprasad B J S, *Civil Eng J*, 5 (2019) 1893.

22 Anandha Kumar S, Sujatha E R, Pugazhendi A & Jamal M T, *Clean Technol Environ Policy*, 25 (2023) 323.

23 Oprea S &Oprea V, *e-Polymers*, 16 (2016) 277.

24 Karami H, Pooni J, Robert D, Costa S, Li J &Setunge S, *TranspGeotech*, 29 (2021) 100585.

25 Munda J, Padhi J & Mohanty S, *Mater Today Proc*, 67 (2022) 1268.

26 Renjith R, Robert D, Setunge S, Costa S & Mohajerani A, *J Clean Prod*, 294 (2021) 126264.

27 Chudzikowski R J, *J SocCosmetChem*, 22 (1971) 43.

28 García-Ochoa F, Santos V E, Casas J A & Gómez E, *Biotechnol Adv*, 18 (2000) 549.

29 Gupta S C, Hooda K S, Mathur N K & Gupta S, *J Appl Polym Sci*, 113 (2009) 2224.

30 Chen R, Zhang L & Budhu M, *J Geotech Geoenviron Eng*, 139 (2013) 1802.

31 Chen C S H & Sheppard E W, *PolymEngSci*, 20 (1980) 512.