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Shear strength enhancement of fine sand soil using Guar Gum biopolymer under varying curing conditions

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Abstract
This study investigates the effect of Guar Gum biopolymer on the shear strength behaviour of fine sand soil, with the aim of evaluating its potential as a sustainable soil stabilization agent. A series of direct shear tests, following ASTM D3080-23, was conducted on Guar Gum-treated soil samples with varying biopolymer concentrations (1%, 3%, and 5%) and water content (10%, 12%, and 15%). Curing durations of 2, 5, and 7 days were applied to assess time-dependent strength development. The shear strength parameters, cohesion (c) and internal friction angle (φ), were evaluated to quantify the improvement in soil performance. The results showed that cohesion increased with higher Guar Gum concentration and longer curing times, with the highest cohesion (0.105 kg/cm²) observed at 5% concentration after 7 days. However, the internal friction angle decreased with prolonged curing, suggesting a shift from the frictional to cohesive strength. Water content had a significant impact, with 10–12% yielding optimal results. At a water content of 12 %, the highest internal friction angle (52°) was recorded after 7 days. Overall, the findings confirm that Guar Gum can significantly enhance the shear strength of fine sand when key parameters are optimized, offering an effective, environmentally friendly alternative to conventional chemical stabilizers in geotechnical applications.

Keywords:
Direct Shear Test;
Fine Sand Soil;
Guar Gum Biopolymer;
Soil Stabilization;

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INTRODUCTION

In geotechnical engineering, the pursuit of sustainable soil improvement methods has become increasingly important in response to the growing environmental concerns. Issues such as soil degradation, erosion, and nutrient depletion have highlighted the need for alternative solutions to improve soil properties while minimizing environmental impact. One promising approach is the use of biopolymers, which are organic compounds derived from natural sources, as environmentally friendly soil stabilizers [1, 2, 3].

Traditionally, soil improvement techniques have been broadly classified into two categories: mechanical and chemical stabilization [4]. Mechanical methods include compaction, vibration, anchoring, and the use of geosynthetics, which typically incorporate cementitious binders to enhance interparticle bonding and reduce pore spaces within the soil matrix [5, 6, 7].

Among the chemical stabilizers, lime and cement are the most commonly used materials [8, 9, 10, 11]. These binders improve the soil strength by forming cementitious compounds through pozzolanic reactions. Other additives, such as bitumen, fly ash, and sodium sulphate, have also been employed for soil stabilization, as reported by [12, 13, 14, 15, 16, 17, 18]. However, the environmental footprint of these traditional binders, particularly in terms of embodied carbon and long-term sustainability, has prompted researchers to explore alternative low-impact solutions such as biopolymers [19, 20, 21, 22].

Biopolymers are naturally occurring polymers synthesized by biological organisms such as fungi, algae, and bacteria through biosynthesis and biodegradation. They are primarily composed of polysaccharides, which are long chains of monosaccharide units linked by glycosidic bonds [23, 24, 25]. Owing to their natural origin and molecular structure, biopolymers are inherently non-toxic and biodegradable, making them environmentally sustainable alternatives to conventional chemical additives [26, 27, 28, 29]. The application of natural biopolymers in civil engineering dates back to the ancient times. Historical records indicate that natural bitumen, straw, and sticky rice were used for construction. A notable example is the use of sticky rice mortar, which remains structurally intact, as a binder in the construction of the Great Wall of China [30].

Recent studies have explored the use of biopolymers, particularly guar gum, for eco-friendly soil stabilization. Yogeshwar and Sonthwal [31] investigated the effectiveness of Guar Gum, a naturally occurring biopolymer, for enhancing the mechanical properties of clay-rich soils. Their study evaluated five different Guar Gum dosages (0.5, 1.0, 1.75, 2.50, and 3.25% by weight of dry soil) to determine the optimal content for soil stabilization. The key geotechnical parameters assessed included the relationship between the optimum moisture content and maximum dry density, California Bearing Ratio (CBR) under both unsoaked and soaked conditions, and unconfined compressive strength (UCS). The results indicated that 1.0% Guar Gum content yielded the most significant improvement across all measured properties, suggesting that it is the optimal dosage for enhancing the strength and stiffness of clayey soils.

Sujatha and Sivaraman [32] evaluated the potential of Guar Gum, a natural polysaccharide, to enhance the geotechnical properties of clay soils. Their findings revealed that Guar Gum-treated soil exhibited behaviour similar to stiff clay, characterized by higher load-bearing capacity and reduced strain at failure. A significant increase in the stiffness modulus was observed with the addition of Guar Gum, indicating an improved resistance to deformation. The increase in strength over time was attributed to the gradual formation of hydrogen bonds between the biopolymer and soil particles. Although biopolymers are generally susceptible to biological degradation, the study noted minimal strength loss, with continued strength development observed over a 90-day curing period.

Usha et al. [33] investigated the use of Guar Gum and Gellan Gum as sustainable biopolymer additives for stabilizing clayey soils. The study involved compaction, unconfined compressive strength, permeability, consistency limits, and consolidation tests using soils treated with varying biopolymer dosages. Biopolymers form hydrogels upon activation, enhancing interparticle bonding and increasing soil strength. The results showed that biopolymer addition increased the dry unit weight, decreased the optimum moisture content, and improved stiffness. Higher biopolymer concentrations reduced permeability due to a lower void ratio. In addition, the treated soils exhibited an increased liquid limit, plastic limit, shrinkage limit, and viscosity. The study concluded that both guar gum and gellan gum significantly improved the mechanical and consistency properties of weak soils.

Despite the growing interest in Guar Gum for sustainable ground improvement, most existing research has concentrated on highly cohesive soils and mechanical properties such as UCS, CBR, and permeability. What has escaped the attention of previous researchers is the specific influence of Guar Gum on shear strength parameters, cohesion, and internal friction angle, which are fundamental to geotechnical analysis and design. Furthermore, past studies have largely neglected fine sand soils, which contain both granular and fine particles and thus represent a distinct soil behaviour profile in which the biopolymer-soil interaction may differ.

From a theoretical standpoint, the novelty of this study lies in its focus on the shear strength behaviour governed by particle interlock and bonding mechanisms, and how Guar Gum, a hydrophilic polysaccharide, modifies these interactions in fine sand soils. Unlike compressive strength, which primarily reflects bulk resistance, shear strength (governed by the Mohr–Coulomb failure criterion) reflects both frictional and cohesive contributions, offering deeper insight into the stabilization mechanism.

This study aims to investigate the effect of Guar Gum biopolymer on the shear strength behaviour of fine sand soil using direct shear tests in accordance with ASTM D3080-23 [34]. This study evaluates the influence of varying Guar Gum concentrations on key shear strength parameters (cohesion and internal friction angle) under different curing and moisture conditions, contributing new insights into the performance of biopolymer-treated mixed-texture soils.

METHOD

The data presented in this study were obtained through a series of controlled laboratory experiments designed to characterize the geotechnical properties of fine sand soil and evaluate its shear strength following Guar Gum biopolymer treatment. Prior to shear strength testing, comprehensive laboratory tests were conducted to determine the basic physical properties of the untreated fine sand. These included measurements of bulk density, dry density, particle density, and grain-size distribution. These baseline tests were essential to ensure sample uniformity and provide a consistent reference for assessing the effects of Guar Gum modification.

Fine sand soil was selected for this study because of its common use in civil and structural engineering applications. Its granular structure and inherently low shear strength make it a suitable candidate for stabilization studies, particularly for assessing the efficacy of natural biopolymer additives. The soil parameters are listed in Table 1.

Guar Gum, a natural polysaccharide derived from the seeds of Cyamopsis tetragonoloba (guar plant), was selected as the biopolymer additive. The materials used in this study were sourced from Lucid Colloids, Ltd. (India) (Figure 1). Guar Gum is known for its hydrophilic and pseudoplastic properties, which enable it to form viscous hydrogels that improve inter-particle bonding and enhance the cohesive behaviour of soil matrices.

Direct shear tests were performed on Guar Gum-treated and untreated soil samples to evaluate the influence of biopolymer content and other variables on the shear strength behaviour. The experimental matrix is expressed as follows.

- Guar Gum concentrations: 1%, 3%, and 5% by dry weight of soil
- Water contents: 10%, 12%, and 15%
- Curing times: 2, 5, and 7 days

The Guar Gum concentrations (1–5%) were chosen based on previous studies reporting effective soil stabilization at low to moderate dosages [31][32], while the selected water contents (10–15%) reflect typical field moisture conditions relevant to soil compaction and stabilization.

Table 1. Table Caption

Parameter	Unit	Value
Maximum Dry Unit Weight	g/cm^3	1.94
Optimum Water Content	%	12
Specific Gravity	-	2.66

The curing times (2–7 days) represent short- to medium-term periods to capture the time-dependent effects of biopolymer hydration and bonding on the shear strength.

Soil and biopolymer mixtures were prepared by thoroughly blending dry Guar Gum powder with soil, then adding water to achieve the target moisture content. The samples were compacted in a shear box to achieve the target dry density corresponding to the maximum dry density obtained from the Standard Proctor test (1.94 g/cm^3). Compaction was performed in three layers, each tamped uniformly with a standard compaction hammer to ensure a consistent density across the sample. The achieved density was verified by measuring the mass and volume of the compacted specimen in the shear box, confirming it was within ±2% of the target dry density. The compacted samples were then cured under controlled conditions for specified durations.

All direct shear tests were conducted in accordance with ASTM D3080-23 standards [34] to ensure procedural consistency and data reliability. The objective of the testing was to determine the peak shear strength and the corresponding shear stress–displacement behaviour of each sample. From the test results, key shear strength parameters, including the cohesion (c) and internal friction angle (φ), were derived using the Mohr–Coulomb failure criterion. A comparative analysis was performed between Guar Gum-amended and control (untreated soil at the same water content) samples to evaluate the effectiveness of Guar Gum in enhancing shear strength.

This study is based on the Mohr–Coulomb failure theory, which defines the shear strength (τ) as a function of cohesion (c) and internal friction angle (φ), expressed as (1).

$$\tau = c + \sigma \cdot \tan(\varphi) \quad (1)$$

where, σ is the normal stress. Traditionally, this framework has been applied to granular and cohesive soils without organic modifications. However, the application of biopolymers such as Guar Gum introduces a new bonding mechanism through hydrogen bonding and hydrogel formation, which can influence both c and φ.

The scientific contribution of this study lies in the application and extension of the Mohr–Coulomb theory to biopolymer-treated fine sand, a soil type that has not been studied extensively. By quantifying how biopolymer concentration, water content, and curing time alter shear strength parameters, this study provides a theory-informed understanding of biopolymer-soil interactions.

Figure 1. Biopolymer Guar Gum

The results also offer a basis for refining existing strength models to account for natural polymer additives in geotechnical designs.

To illustrate the research process and the theoretical foundation of this study, a conceptual flowchart is presented in Figure 2. This framework outlines the sequential steps from identifying the problem of low shear strength in fine sand soil to the selection of input variables, namely, Guar Gum concentration, water content, and curing time, followed by direct shear testing in accordance with ASTM D3080-23 [34].

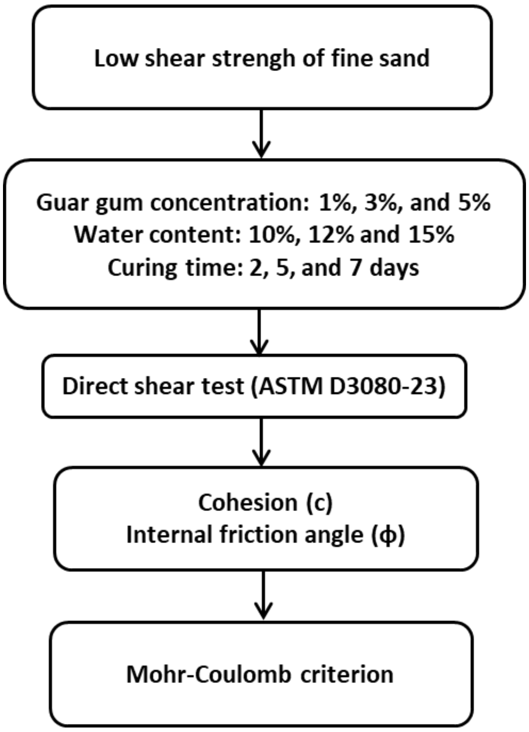

Figure 2. Conceptual Framework of the Research and Theoretical Basis

The output parameters derived from the tests, cohesion (*c*), and internal friction angle (*φ*), were interpreted using the Mohr–Coulomb failure criterion. The framework also highlights the theoretical contribution of this study, namely the application and extension of classical shear strength theory to biopolymer-treated fine sand soils. This approach provides a structured basis for evaluating the effects of natural polymers on soil behaviour, offering insights into the interplay between biopolymer dosage, moisture content, curing time, and shear strength development.

RESULTS AND DISCUSSION

This section presents and analyses the effects of the Guar Gum biopolymer on the shear strength parameters of fine sand soil, with a specific focus on two key variables: Guar Gum concentration and water content. Each parameter was investigated for multiple curing durations (2, 5, and 7 d) to evaluate the time-dependent behaviour of the treated soil. The results were derived from direct shear tests, and the shear strength parameters, namely, cohesion (c) and internal friction angle (φ), were extracted using the Mohr–Coulomb failure criterion. The influence of Guar Gum concentration is discussed in the first subsection, followed by an analysis of water content in the second subsection, which highlights the combined effects of dosage, moisture, and curing on overall strength improvement.

Effect of Guar Gum Concentration

This subsection investigates the influence of the Guar Gum concentration on the shear strength behaviour of fine sand soil, with a constant water content of 10% maintained across all samples. Three different biopolymer concentrations (1, 3, and 5% by dry weight of soil) were selected to evaluate the dose-dependent response of the soil to Guar Gum treatment. The analysis was conducted under three distinct curing durations of 2, 5, and 7 days to observe time-dependent changes in strength. The direct shear test results were used to determine the peak shear strength, cohesion (c), and internal friction angle (φ) of the treated soils.

Figure 3 illustrates the effect of Guar Gum concentration and curing time on the cohesion of fine sand soil at a constant water content of 10%. A clear trend emerges: increasing the biopolymer content and extending the curing time generally enhance soil cohesion. However, the interaction was not linear, indicating a complex relationship influenced by the biopolymer-soil bonding mechanisms and curing dynamics.

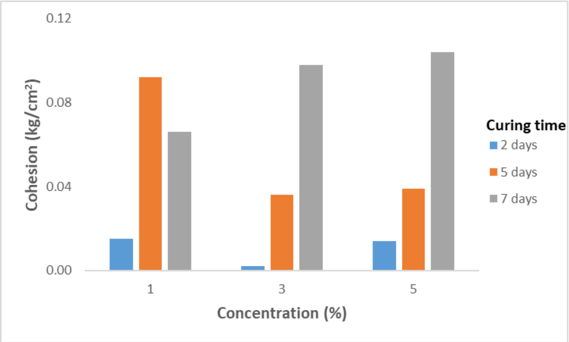

Figure 3. Cohesion of fine sand soil under different Guar Gum concentrations

At 2 days of curing, cohesion remained low across all Guar Gum concentrations, with the highest value (~0.025 kg/cm²) observed at 5%. This early-stage performance suggests insufficient time for full hydration and polymer network formation. At this point, Guar Gum may act more as a lubricant than a binder, offering minimal mechanical interlocking between soil grains.

After 5 days of curing, the cohesion at 1% Guar Gum sharply increases to approximately 0.09 kg/cm², the highest among all curing periods at this concentration. This suggests that at lower dosages, the polymer is optimally dispersed, allowing uniform hydrogel formation that bridges the particles and enhances cohesive strength. However, increasing the dosage to 3% and 5% at the same curing time unexpectedly resulted in a reduced cohesion (~0.035 kg/cm²). While this trend may indicate that excessive Guar Gum leads to agglomeration and non-uniform bonding, it is also possible that incomplete or uneven mixing at higher polymer contents contributed to localized weak zones within the soil matrix. Although consistent manual mixing procedures were applied in this study, the lack of microstructural analysis prevented a definitive confirmation of the mechanism. Nonetheless, these findings highlight the importance of optimizing biopolymer dosage and mixing techniques to ensure effective stabilization.

After 7 days of curing, the behaviour changed significantly. A consistent increase in cohesion was observed as the Guar Gum concentration increased, reaching a maximum of approximately 0.105 kg/cm² at 5%. This trend reflects the time-dependent nature of the hydrogen bonding and hydrogel maturation. During extended curing, Guar Gum undergoes full hydration, forming a more stable, continuous matrix that fills voids and reinforces the interparticle structure.

This longer curing duration allows for more effective biopolymer-soil interactions, particularly at higher dosages, where delayed hydration and diffusion are otherwise limiting factors.

These findings provide new insights into biopolymer stabilization mechanisms by demonstrating that the effectiveness of Guar Gum is not only dose dependent but also strongly influenced by curing time. More importantly, they indicated that an optimal combination of 1–3% Guar Gum content with a curing period of 5–7 days maximizes interparticle bonding and, hence, soil cohesion. From a theoretical standpoint, these results suggest that, in biopolymer-treated soils, the cohesion term (c) in the Mohr–Coulomb failure envelope can be significantly enhanced through polymer-induced bonding, provided that the curing conditions support complete gel formation and integration with the soil matrix.

Figure 4 illustrates the variation in the internal friction angle of the Guar Gum-treated fine sand as a function of both the biopolymer concentration and curing time. The results highlight a nonlinear relationship in which the interplay among gel formation, particle interactions, and curing dynamics governs the frictional behaviour of the treated soil.

At 1% Guar Gum concentration, the friction angle was the highest after 2 days of curing (~35°), indicating that at early stages, the biopolymer begins to form thin films or weak gel networks that slightly enhance interparticle interactions. However, as curing progressed to 5 and 7 d, a notable decline in the friction angle was observed, reaching a minimum (~20° at 5 d). This reduction may be attributed to the onset of excessive lubrication caused by immature gel formation, where water remains entrapped within partially hydrated polymer chains, thereby reducing effective grain-to-grain contact.

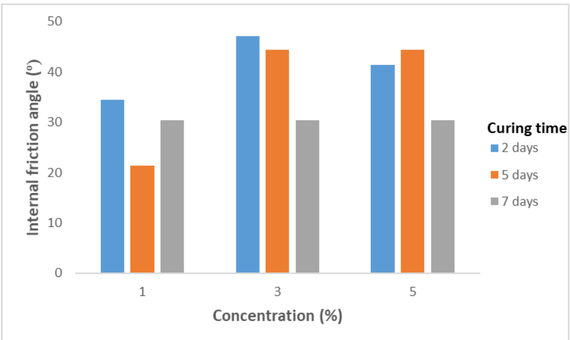

Figure 4. Friction angle of fine sand soil with different Guar Gum concentrations

Effect of Water Content

This subsection investigates the influence of water content on the shear strength behaviour of fine sand soil treated with a constant 1% concentration of the Guar Gum biopolymer. Water plays a critical role in biopolymer–soil interactions and affects the hydration, gel formation, and polymer distribution within the soil matrix. To evaluate this effect, three different water contents (10 %, 12 %, and 15% by weight) were considered, and direct shear tests were performed after curing durations of 2, 5, and 7 days.

Figure 5 presents the influence of water content on the cohesion of fine sand soil treated with 1% Guar Gum for different curing times. The results clearly demonstrate that water content plays a critical role in modulating the cohesive strength of biopolymer-treated soil by influencing the polymer's hydration behaviour and distribution within the soil matrix.

At 10% water content, the highest cohesion values were recorded across all curing periods, with a peak value of approximately 0.09 kg/cm² observed at 5 days of curing. This indicates that 10% moisture provides the optimal hydration conditions for Guar Gum activation, promoting the formation of a well-structured hydrogel network that effectively bridges soil particles and enhances interparticle bonding. The improvement at this water content aligns with the fundamental behaviour of hydrophilic polymers, which require a balanced moisture environment to swell and form effective gel matrices without over-dilution.

At 12% water content, cohesion values were moderate at early curing stages (2–5 days) but dropped significantly by 7 days. This suggests that while initial hydration at 12% supports some gel development, prolonged curing under higher moisture conditions may lead to excess water interfering with matrix consolidation.

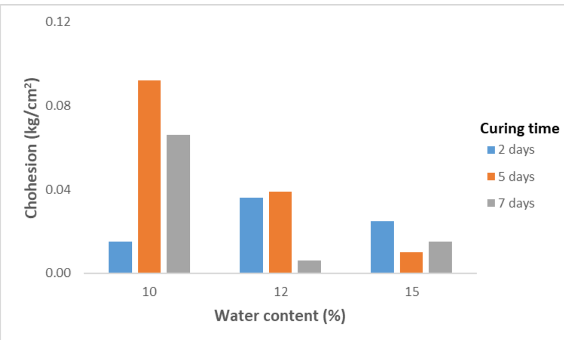

Figure 5. Cohesion of fine sand soil with different water contents

Overhydration likely prevents Guar Gum from forming strong interparticle links, dilutes the gel concentration, and weakens the structural integrity of the soil–polymer composite. Based on these findings, the optimal moisture balance for 12% moisture was observed at 2–5 d of curing, beyond which cohesion decreased, reflecting Guar Gum's sensitivity to maintaining proper moisture levels during curing.

At 15% water content, the lowest cohesion values were consistently observed across curing durations. This indicates that excessive moisture undermines the stabilizing effect of Guar Gum, likely owing to a combination of dilution and pore water pressure retention. High water content may hinder polymer-to-particle contact and promote dispersion rather than gelation, resulting in a poorly connected matrix. Moreover, the persistent presence of excess water reduced the effective stress in the soil, further diminishing the mobilized shear strength.

From a geotechnical perspective, these findings highlight that water content directly influences the cohesion component (c) in the Mohr–Coulomb failure criterion, not only by controlling polymer hydration but also by determining the soil matrix's physical structure and bonding potential. The results underscore the existence of an optimum moisture threshold of 10%, which maximizes the bonding capacity of the biopolymer and enables effective load transfer between soil particles.

This study provides new insights into how moisture-driven gel behaviour interacts with curing kinetics to determine the mechanical outcome of biopolymer-treated soils. This emphasizes the importance of moisture management in field applications, especially for stabilizing fine-grained or mixed soils with natural polymers, where underhydration or overhydration can significantly affect the performance.

Figure 6 demonstrates the influence of water content on the internal friction angle of fine sand soil treated with 1% Guar Gum, measured for curing durations of 2, 5, and 7 days. The results revealed that water content is a key variable affecting the frictional component of shear strength, and its impact is strongly dependent on the balance between hydration, polymer distribution, and curing time.

At 10% water content, the friction angle peaked early at ~35° after 2 days, but then declined to ~22° after 5 days and recovered slightly to ~30° after 7 days. This suggests that although 10% moisture initially facilitates partial hydration and some degree of interparticle bonding, extended curing may lead to

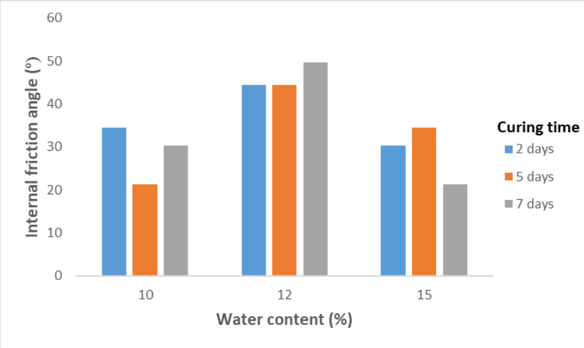

Figure 6. Friction angle of fine sand soil with different water contents

progressive gel formation that fills the pore spaces and smooth particle surfaces. This process reduces the intergranular roughness and diminishes the sliding resistance, thus lowering the friction angle because cohesive mechanisms begin to dominate over frictional mechanisms.

In contrast, at 12% water content, the friction angle remained consistently high across all curing durations, ~45° at 2 and 5 d, and reached ~52° at 7 d, the highest recorded value in this study. This indicates that 12% moisture provides optimal hydration conditions for Guar Gum activation, resulting in a uniform distribution of the hydrogel throughout the soil matrix. Under these conditions, the gel binds particles and preserves intergranular contact, enabling the development of a structurally robust matrix that maintains frictional resistance, even as cohesion increases. Extended curing appears to strengthen this effect, likely through improved polymer-soil adhesion and network maturity.

At 1 water content of 15 %, the internal friction angle ranged from ~30–35° during early curing, but dropped sharply to ~22° after 7 days. This decline reflects the negative effects of excessive moisture, which can oversaturate the system, leading to biopolymer dilution and reduced inter-particle friction. As water content increases beyond the optimal range, Guar Gum may act more as a dispersant than a binder, leading to a loss of shear resistance due to reduced particle interlock and elevated pore-water pressure.

These findings highlight a clear cause-and-effect relationship between the water content, curing time, and shear strength mechanisms in biopolymer-treated soils. At ideal moisture levels (12%), a synergistic balance was achieved between hydration, interparticle contact, and gel development, maximizing both the frictional and cohesive contributions to the shear strength. By contrast, under- or over-saturation disrupts this balance, leading to performance deterioration, particularly for longer curing durations.

From a theoretical perspective, the results suggest that the internal friction angle (φ), as defined in the Mohr–Coulomb failure criterion, is not static in biopolymer-treated soils, but dynamically evolves with curing and moisture conditions. This study advances the understanding of biopolymer–soil interactions by demonstrating that frictional strength is sensitive to the hydration state and that optimal water content is crucial not only for cohesion but also for maintaining shear resistance in stabilized fine-grained soils.

Comparison with previous research

This subsection presents a comparative analysis of the current study's findings with those of previous studies on biopolymer-treated soils, particularly those incorporating Guar Gum. The comparison focuses on the trends in shear strength parameters (cohesion and internal friction angle) under varying Guar Gum concentrations, water contents, and curing durations. In doing so, the discussion highlights both the alignment and divergence of this study's outcomes with the global literature, thereby reinforcing its scientific contribution.

The observed increase in cohesion with higher Guar Gum concentration and extended curing duration in this study aligns with the findings reported by Sujatha and Sivaraman [32], who demonstrated time-dependent strength gain in clayey soils treated with Guar Gum, attributed to progressive hydrogen bonding and hydrogel network formation. Similarly, Yogeshwar and Sonthwal [31] identified 1% Guar Gum as the optimal dosage for improving unconfined compressive strength (UCS) and California Bearing Ratio (CBR), consistent with the peak cohesion observed in this study at 1% Guar Gum after 5 days of curing. However, while previous studies have focused predominantly on cohesive soils, the current study extends these observations to fine sand soil and specifically investigates the shear strength behaviour, offering a more application-oriented evaluation relevant to geotechnical design.

Overall, this study builds on and extends the existing literature by applying shear-strength-based evaluation to fine sand soil, a material type that has received limited attention in biopolymer research. The findings provide a more nuanced understanding of how Guar Gum interacts with mixed soil textures and contribute to the broader body of work aimed at incorporating sustainable, bio-based additives into mainstream soil stabilization practices.

CONCLUSION

This study investigated the influence of the Guar Gum biopolymer on the shear strength behaviour of fine sand soil through a series of direct shear tests conducted in accordance with ASTM D3080-23. The experimental program focused on evaluating the effects of varying Guar Gum concentrations (1%, 3%, and 5%) and water content (10%, 12%, and 15%) under different curing durations (2, 5, and 7 d), with shear strength parameters (cohesion and internal friction angle) used as key indicators of soil performance.

The results demonstrated that Guar Gum concentration and curing time significantly affect soil cohesion. At a constant water content of 10%, the cohesion increased with curing time, with the highest value observed at 5% Guar Gum after seven days. However, excessive concentrations during short curing periods can lead to biopolymer agglomeration and suboptimal bonding. The internal friction angle was generally the highest at 3% concentration and shorter curing times, suggesting that an optimal balance between the frictional and cohesive mechanisms is necessary to maximize the shear resistance.

In terms of water content, 10–12% moisture yielded the most favourable results. The highest cohesion was achieved at 10% water content and 5 days of curing, whereas the internal friction angle peaked at 12% water content after 7 days. Higher moisture levels (15%) were found to reduce both the cohesion and friction angle, likely owing to the dilution of the biopolymer matrix and the disruption of interparticle bonding.

Overall, the findings confirm that Guar Gum is an effective and environmentally friendly soil stabilizer for fine sand soils when key parameters such as biopolymer dosage, moisture content, and curing duration are optimized. Based on these results, it is recommended to use a Guar Gum content of 1–3% by dry weight with a moisture content of 10–12% and a curing period of 5–7 days to achieve maximum improvement in the shear strength parameters. This study provides valuable insights into the application of biopolymer-based stabilization techniques in geotechnical engineering, offering a sustainable alternative to conventional chemical stabilizers.

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AUTHOR CONTRIBUTION

RS prepared the manuscript and data analysis, MDK conducted the experiment, IGMS reviewed the manuscript, and AS reviewed the manuscript.

DATA AVAILABILITY

Experimental results and analysis https://zenodo.org/records/15200932.

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