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Improving the Compressive Strength of Sandy Soil via the use of Biopolymers and Fibers

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Abstract

Soil strength enhancement is essential for rapid urbanization, but conventional stabilizers such as cement have significant environmental impacts. This study investigated the combined effects of cross-linked biopolymers (xanthan gum and starch) and fibers (jute and polypropylene) on the unconfined compressive strength (UCS) and ductility of sandy soil. The sand was treated with various combinations of xanthan gum (0.5%), starch (3–6%), and fibers (0.5–1.0%), compacted at the optimum moisture content, and cured for 7, 14, and 28 days. Starch cross-linked with XG attained a compressive strength of 1.60 MPa, which was more than three times greater than that of XG alone (0.51 MPa) and significantly exceeded the strength of the cement-treated controls (1.09 MPa). While fibers had minimal influence on compressive strength, they significantly increased the tensile strain capacity, with polypropylene fiber-reinforced samples achieving 23.6% greater ductility than their jute-reinforced counterparts. Statistical analysis confirmed that all the biopolymer fiber mixtures except xanthan gum alone presented significantly greater strength and strain capacity than did the cement-treated soil ($p < 0.001$). These findings demonstrate that cross-linked biopolymers with fiber reinforcement are not only effective, sustainable alternatives to cement but also superior strength enhancers for soil improvement applications.

1. Introduction

Rapid urbanization often requires construction on soils with inadequate engineering properties. Poor-quality soils with low strength and stability can lead to pavement deformation, slope failure, and structural instability. Soil improvement techniques are therefore essential for enhancing physical and mechanical properties such as shear strength and bearing capacity. Cement has traditionally been used as a stabilizing agent because of its effectiveness and relatively low cost [1]. However, cement production has significant environmental consequences, including high carbon emissions and degradation of soil quality [2]. Consequently, interest in sustainable alternatives is increasing.

Biopolymers offer a sustainable solution because they are eco-friendly and abundant in nature [3]. Biopolymers are attracting research interest because they are simpler and more effective for soil stabilization [4]. Previous studies have demonstrated that biopolymers can significantly improve soil strength, durability, and resistance to deformation. These improvements are attributed to the formation of gel-like structures that bind soil particles and reduce pore connectivity.

Biopolymers have been shown to improve the compressive strength of soil at very low soil-to-biopolymer ratios (w/w), e.g., 0.5% [5]. It is suitable for earthen slope reinforcement, as demonstrated by successful durability tests [6]. In both split tensile and direct shear tests, biopolymers performed well [7, 8]. However, the addition of biopolymers can reduce soil permeability excessively by tightening the soil structure. They attach to the particle surface and pull it closer. The biopolymer gel also fills open pores and limits connected voids [9].

Among various biopolymers, some have been widely studied because of their strong binding capacity and ability to increase soil strength. Xanthan gum (XG) and guar gum have been reported to be effective at enhancing soil properties [10]. Gellan gum and agar gum have similar properties, including thermogelation and significant efficiency in strengthening soils [11]. The application of chitosan as an additive to earthen constructions contributes positively to water durability [12]. The effects of biopolymers on the physical properties of soil are dependent mainly on the biopolymer type, soil type, biopolymer content, curing time, thermal treatment, and mixing method [13]. The existence of biopolymers can improve soil geotechnical properties, which shows great potential for enhancing soil strength [14] and improving soil properties.

In general, biopolymers are more expensive than conventional soil stabilizers and inorganic binders (e.g., cement). However, considering global greenhouse gas reduction efforts (e.g., carbon emission trading), biopolymers will become remarkably competitive in soil treatment; e.g., for a unit amount (1 Mg) of soil treatment, 0.5% XG is only 3.6% more expensive than 10% cement [15]. Currently, biopolymers are relatively expensive because they are primarily produced for the food, agriculture, and pharmaceutical industries. As their use in geotechnical applications expands, economies of scale are expected to lower their cost.

In addition to biopolymers, fibers are commonly used to improve ductility and tensile resistance in soils. Natural fibers such as jute fibers are biodegradable and environmentally friendly, whereas synthetic fibers such as polypropylene fibers offer durability and chemical resistance.

To the authors' knowledge, the literature on the interaction between fibers and biopolymers remains notably sparse. Additionally, studies examining the effects of combining two different biopolymers to enhance soil engineering properties are lacking, which presents a novel opportunity for improved soil techniques. Consequently, there is a gap in understanding the mechanical behavior when two types of biopolymers and fibers are mixed. Addressing these gaps will provide a quantitative understanding of whether cross-linked biopolymers combined with fibers can achieve mechanical performance comparable to or better than that of cement while offering environmental advantages such as reduced CO_2 emissions and the use of renewable, locally sourced materials. These findings support the adoption of sustainable, bio-based soil stabilizers in geotechnical engineering.

2. Materials and methods

2.1 Materials

Sand was collected from the Balu River in Dhaka, Bangladesh, at a depth of 3 m. This depth was selected to obtain clean, uniform sand with minimal organic content and to represent subsurface conditions relevant to engineering applications. Fig. 1 shows the grain size distribution curve of the sand. The sand used in this study was classified as poorly graded sand (SP) according to the following standards: ASTM

D6913-17 (the standard sieve sizes per ASTM D6913-17 are No. 4 (4.75 mm), No. 10 (2.00 mm), No. 16 (1.18 mm), No. 30 (0.600 mm), No. 50 (0.350 mm), No. 100 (0.150 mm), No. 200 (0.075 mm), and a pan.

Xanthan gum is a biopolymer derived from Xanthomonas campestris. It is an anionic extracellular heteropolysaccharide usually produced by gram-negative bacteria of the genus Xanthomonas during aerobic fermentation. Xanthomonas campestris produces commercial Xanthan gum with the required rheological properties. It is one of the most widely used industrial gums, with an increase in demand and production of 5% to 10% per year [16].

Starch is a very important and widely distributed natural product that occurs in the leaves of green plants, seeds, fruits, stems, roots, and tubers. They serve as a chemical energy source for the sun and are the primary source of energy for organisms on Earth [17]. Its attributes include renewability, biodegradability, cost-effectiveness, biocompatibility, and nontoxicity [18].

Jute fiber is an excellent reinforcing agent. Polypropylene is nonbiodegradable and can withstand aggressive chemical exposure when it is placed inside a soil medium [19].

2.2 Specimen Preparation

The sand was oven-dried and sieved through a 0.35 mm sieve. Two biopolymers and two fiber types were added to the dry soil in the proportions shown in Table 1. The concentrations of xanthan gum and starch ranged from 0.5% and 3% to 6%, respectively, while the fiber concentrations were maintained between 0.5% and 1%. The dry mixing methodology, as proposed by Soldo and Miletic (2019), was implemented. Dry mixing is more effective than wet mixing when the aim is to strengthen the material with xanthan gum powder [20]. The xanthan gum or starch powder, or both, and fiber were initially mixed uniformly with the dry soil for 15 minutes at 1000 RPM in a blender (Fig. 2.e). The optimal water content (determined via the Proctor test) was mixed with the sand, biopolymers, and fiber mixture.

To prepare the samples, the mixture was placed in a cylindrical mold. Each sample was compacted in three layers with a standardized hammer with a mass of 2.5 kg. The hammer was released 25 times from a height of 30 cm to fall freely on each soil layer. The mold diameter was 38 mm, and the length was 76 mm [21] (Fig. 2.f). Three parallel samples were made for each treated sand sample to minimize errors, and the mean value was used for analysis.

2.3 Likely Sources of Errors from the Specimen

The optimum water content was determined via the modified Proctor test before the final sample was made for use in the UCS test. To improve bonding, the water content was slightly adjusted (±5 g). The samples were cured at room temperature, which could fluctuate by ±5 °C.

Table 1. Combinations of biopolymers and fibers used in the unconfined compressive strength test (all amounts are in grams per kilogram of dry sand)

Test Group[a]	Xanthan gum (g/kg)	Starch (g/kg)	Polypropylene (g/kg)	Jute (g/kg)	Water (g/kg)	Cement (g/kg)
XG	5	0	0	0	105	0
XGS	5	60	0	0	130	0
XGP	5	0	5	0	200	0
XGJ	5	0	0	5	180	0
XGSP	5	60	5	0	200	0
XGSJ	5	60	0	5	180	0
XGSP1	5	60	10	0	220	0
XGSJ1	5	60	0	10	160	0
Cement	0	0	0	0	150	100

[a] Composition of the stabilized sand mixtures. Test groups are named according to their constituents: XG (xanthan gum), S (starch), P (polypropylene fibers), and J (jute fibers). All the mixtures contained sand and water, with additional additives as specified. For example, XGS contains xanthan gum, starch, sand, and water; XGP contains xanthan gum, polypropylene fibers, sand, and water.

2.4 Experimental Design and Statistical Analysis

2.4.1 Experimental Design

This study employed a factorial design to systematically investigate the individual and combined effects of XG, starch (S), and two fiber types (polypropylene, P; jute, J) on the engineering properties of sand. Eight primary mixture groups were formulated on the basis of the presence/absence and dosage of these additives (Table 1). A follow-up group of cement-treated controls (cement) was also included for comparison.

2.4.2 Replication and Randomization

For each of the nine primary mixture groups, three identical cylindrical samples (n=3 replicates) were fabricated for unconfined compression testing at each curing age (7, 14, and 28 days). The preparation order for all the samples was randomized to prevent systematic bias from temporal changes in laboratory conditions (e.g., humidity, mixer temperature).

2.4.3 Data analysis

The unconfined compressive strength (UCS) test is an appropriate test for determining the compressive strength of soil. For the determination of compressive strength, the axial load was applied with a strain rate of 1.5%/min, as per ASTM D2166. The unconfined compressive strength (UCS) was calculated as the peak axial load divided by the original cross-sectional area. The result for each mixture at each curing age was reported as the mean ± standard deviation of the three replicates. To determine the optimum moisture content and examine the compressive strength of the stabilized samples, a series of standard Proctor tests and UCS tests for the given percentages of XG, starch, and fiber-treated soil were carried out.

2.4.4 Statistical comparison of laboratory results

The significance of the differences in the mean UCS between the mixture groups at each curing age was evaluated via one-way analysis of variance (ANOVA). When ANOVA indicated a significant overall effect ($p < 0.05$), Tukey's honestly significant difference (HSD) post hoc test was applied for pairwise comparisons between all groups. All the statistical analyses were conducted via Python (version 3.9) with SciPy and stats model libraries at the 95% confidence level ($\alpha = 0.05$).

3. Results

3.1 Soil classification, specific gravity, modified Proctor test, natural water content, and relative density test

The sand used in this study was classified as poorly graded sand (SP), characterized by effective sizes of D_{10} = 0.125 mm (the diameter at which 10% of the particles are finer), D_{30} = 0.18 mm, and D_{60} = 0.24 mm. The derived coefficients of uniformity ($C_U = D_{60}/D_{10} = 1.99$) and curvature ($C_C = (D_{30})^2/(D_{10} \times D_{60}) = 0.98$), along with a low fines content of 1.67%, confirm this classification. The soil has a specific gravity (G_s) of 2.694. Standard Proctor compaction yielded an optimum moisture content of 16%, a maximum dry density of 1.63 g/cm³, and a minimum dry density of 1.27 g/cm³. The material was tested at a natural moisture content of 2%.

3.2 Effects of Xanthan gum on compressive strength with curing time

Fig. 3 shows that the biopolymer has a major effect on strength. When cured in air for 28 days, XG forms gel films that firmly bind soil particles and fibers, increasing adhesion [19]. This enhanced interparticle adhesion contributes to the observed increase in compressive strength. However, xanthan gum films progressively shrink over time, leading to reduced compressive strength and increased brittleness. As water evaporates from the gel matrix, the loss of internal moisture causes volumetric shrinkage, which in turn creates voids between soil particles and weakens interparticle bonding. This process explains the initial increase in strength observed up to 14 days, followed by a decrease of approximately 26–32% at 28 days, as illustrated in Figure 3(a–c).

Statistical analysis confirmed that the reduction in strength between 14 and 28 days is significant. A one-way ANOVA conducted on XG-treated samples across three curing periods revealed a notable effect of the curing time on the unconfined compressive strength (F = 9.87, p = 0.013). Post hoc Tukey HSD comparisons revealed no significant difference between the 7-day (mean = 0.60 MPa) and 14-day (mean = 0.70 MPa) strengths (p = 0.139). However, the 14-day strength was significantly greater than the 28-day strength (mean = 0.51 MPa, p = 0.010). The difference between the 7-day and 28-day strengths was also not statistically significant (p = 0.153). These findings indicate that xanthan gum films experience notable shrinkage and embrittlement between 14 and 28 days of air curing.

3.3 Effects of the cross-linking of biopolymers on the compressive strength

Figure 4 shows the variation in compressive strength with increasing curing time for different biopolymer—fiber combinations under cross-linked conditions. Compared with XG alone or XG combined with fibers, the incorporation of starch into XG nearly doubled the compressive strength. Previous studies [6] have shown that XG can improve compressive strength. However, the addition of starch alongside XG and fibers further enhances the strength of the treated soil.

When XG is used alone, the compressive strength typically peaks at approximately 14 days and subsequently decreases by approximately 30% at 28 days. In contrast, when starch is cross-linked with XG, the compressive strength continues to increase for up to 28 days. This improvement is attributed to the highly hydrophilic nature of starch, which slows the evaporation of retained water and reduces shrinkage of the XG matrix. As a result, structural integrity is better preserved, leading to significantly higher strength and preventing the decline observed in XG-only samples.

The compressive strength enhancement provided by starch cross-linking was statistically validated. One-way ANOVA of the 28-day UCS data revealed highly significant differences among the nine mixture groups (F = 24.26, p < 0.001). Post-hoc Tukey HSD tests were conducted to identify specific pairwise differences and perform statistical comparisons.

The addition of starch with xanthan gum resulted in a substantial and statistically significant increase in strength. The XGS mixture (mean = 1.427 MPa) resulted in a significantly greater UCS than did the baseline XG mixture (mean = 0.517 MPa, p = 0.0003). Similarly, mixtures containing both starch and fibers achieved even greater strengths: XGSJ (mean = 1.600 MPa) and XGSP (mean = 1.450 MPa) were both significantly stronger than XG (p < 0.001 for both). These findings indicate that the addition of starch effectively enhances the compressive strength performance of XG.

Notably, several biopolymer-treated mixtures performed comparably to or better than the cement control (cement, mean = 1.087 MPa). XG was not significantly different from Cement (p = 0.460), whereas XGS, XGSJ, XGSP, XGSJ1, and XGSP1 (Fig. 5) significantly exceeded the cement control (p < 0.001). These findings demonstrate the potential of cross-linked biopolymers as sustainable alternatives to traditional stabilizers.

On the basis of Tukey's HSD test, the mixtures were grouped into statistically distinct subsets. The lowest strength (group A) group comprised XG, XGJ, XGP, and cement (mean ≈ 0.48–0.93 MPa). The intermediate (group B) group included cement, XGS, XGSJ, and XGSP (mean ≈ 1.45–1.60 MPa). The highest strength (group C) group consisted of XGSJ1 and XGSP1 (mean ≈ 1.58–1.66 MPa).

3.4 Influence of fibers

3.4.1 Influence of fibers on compressive strength

Jute-reinforced samples (XGJ, XGSJ) presented slightly greater mean unconfined compressive strength (UCS) values (Fig. 4) than did their polypropylene-reinforced counterparts (XGP, XGSP); however, these differences were not statistically significant (XGJ vs. XGP: p = 1.000; XGSJ vs. XGSP: p = 0.767). Notably, when combined with starch, both fiber types produced a statistically significant improvement in strength relative to the untreated XG baseline.

Moreover, increasing the fiber content from 0.5% to 1.0% (XGSJ vs. XGSJ1 and XGSP vs. XGSP1 in Fig. 5) did not yield a statistically significant increase in UCS (p = 0.141). This result indicates that a lower fiber dosage is sufficient to achieve effective strength enhancement.

3.4.2 Influence of fibers on ductility

Fiber inclusion significantly improved ductility by increasing the postpeak strain capacity and delaying crack propagation. The influence of these factors on the tensile strain capacity was evaluated via one-way ANOVA and Tukey's HSD post hoc tests (α = 0.05). The analysis revealed significant differences among the mixture groups ($F(8,18) = 19.65$, $p < 0.001$), with the results summarized in Fig. 5. Compared with the biopolymer-only treatments, the incorporation of fibers increased the tensile strain. XGP and XGJ achieved more strain than XG alone (0.0337 and 0.0288 vs. 0.0233), although these differences were not statistically significant (XGP vs. XG: p = 0.500; XGJ vs. XG: p = 0.966). No significant differences were detected between the polypropylene and jute fiber counterparts:

XGP vs. XGJ: p = 0.981

XGSP vs. XGSJ: p = 0.106

XGSP1 vs. XGSJ1: p = 0.950

These results indicate that both fiber types provide comparable tensile enhancements. Increasing the fiber content from 0.5% to 1.0% increased the mean strain values (XGSP1: 0.0585 vs. XGSP: 0.0516; XGSJ1: 0.0526 vs. XGSJ: 0.0363), but these differences were not statistically significant (p = 0.891 and p = 0.074, respectively). The near-significant p value for jute (p = 0.074) suggests a potential trend that warrants further investigation.

3.4.3 Comparison with cement control

All the fiber-reinforced biopolymer mixtures except XG demonstrated significantly greater tensile strains than did the cement-treated sample (cement, mean = 0.0137) (Fig. 5).

XGSP1, XGSJ1, XGSP: $p < 0.001$

XGSJ: $p = 0.006$

XGP: $p = 0.017$

XGJ: $p = 0.116$ (not significant)

XG: $p = 0.592$ (not significant)

Notably, XGSP1, XGSJ1, and XGSP achieved approximately four times greater strain capacities than did the cement-treated samples.

In summary, fibers contribute to tensile strain enhancement, but a statistically significant improvement only occurs when starch is added with Xanthan gum (XGSP, XGSJ). Fiber type does not significantly influence outcomes, offering flexibility in material selection on the basis of sustainability or economic considerations.

Figure 6 illustrates the role of polypropylene fibers in resisting crack development within the XGP sample.

4. Discussion

4.1 Synergistic strength enhancement by biopolymer cross-linking

The addition of starch to xanthan gum-treated sand dramatically increased the unconfined compressive strength (UCS), with the XGS mixture reaching more than three times the 28-day strength of xanthan gum alone. This finding is consistent with the mechanism proposed by [21], who attributed the initial strength gain in xanthan gum-stabilized soils to the formation of hydrogel films that bind particles. However, those same films shrink as water evaporates, creating microcracks and causing the 26–32% strength loss we observed in XG samples between 14 and 28 days. Starch is strongly hydrophilic and retains water within its granular structure [17, 18]. When cross-linked with xanthan gum, starch likely slows the dehydration of the composite gel, thereby limiting shrinkage cracking and preserving the continuity of interparticle bonds. This interpretation explains why the 28-day UCS of XGS (1.43 MPa) not only exceeded that of XG (0.52 MPa) but also continued to increase with increasing curing time, whereas XG alone decreased. Other authors have reported that xanthan gum alone can achieve UCS values of approximately 0.8–1.0 MPa in sand after 28 days [5, 14]. Our XG result lies at the lower end of that range, probably because of the relatively low biopolymer dosage (0.5%) and the use of air curing, which accelerates film drying. The cross-linked XGS system, however, attained a UCS (1.43–1.60 MPa) that

surpassed most published values for biopolymer-treated cohesionless soils, including those stabilized with 10% cement (1.09 MPa in this study).

The statistical analysis confirmed that starch content had a highly significant effect on UCS ($p < 0.001$), and post-hoc comparisons revealed that XGS, XGSJ, XGSP, XGSJ1, and XGSP1 all significantly outperformed both the XG control and the cement control. This finding demonstrates that cross-linking two biopolymers can produce a binder that is not only environmentally friendlier than cement but also mechanically superior.

4.2 Fibers: limited effect on compressive strength, pronounced improvement in ductility

Fiber reinforcement did not significantly alter the peak UCS of any mixture. Even doubling the fiber content from 0.5% to 1.0% yielded no statistically detectable strength increase ($p = 0.141$). This outcome is consistent with previous reports that fibers mainly improve postpeak behavior rather than prepeak stiffness or peak stress in cemented soils [20]. Nevertheless, both jute and polypropylene fibers markedly enhanced the tensile strain capacity (ductility). All fiber-containing mixtures that also included starch presented strain capacities three to four times greater than those of the cement-treated sand ($p < 0.001$). This behavior is attributed to the crack-bridging effect, which is visually evident in Fig. 6, where fibers stretch across developing cracks, transferring stress and allowing the material to deform extensively before complete failure.

Interestingly, the strain capacity of the polypropylene-reinforced samples was 23.6% greater than that of their jute-reinforced counterparts, although the difference was not statistically significant ($p = 0.106–0.950$ depending on the mixture). The absence of a significant difference between fiber types is actually a practical advantage: it provides flexibility to choose between a synthetic, durable fiber and a renewable, biodegradable fiber on the basis of project-specific sustainability goals without compromising ductility.

4.3 Comparison with cement-treated soil

All the biopolymer fiber mixtures except XG and XGJ significantly exceeded the UCS and strain capacity of the cement control ($p < 0.001$ for XGS, XGSP, XGSJ, and their higher fiber variants). Even the XG mixture, while statistically comparable to cement in UCS ($p = 0.460$), exhibited higher tensile strain (not significant). The clear superiority of cross-linked systems underscores that the combination of biopolymers and fibers can replace cement in applications where strength and ductility are required while avoiding the high CO_2 footprint of cement production [2]. The cost barrier is narrowing at the dosages used here (0.5% xanthan gum + 6% starch vs. 10% cement); the current price difference is modest, and large-scale adoption in geotechnical engineering would likely drive costs down further [15].

4.4 Practical implications and study limitations

These findings have immediate relevance for the stabilization of granular sub-bases, embankments, and temporary erosion-control structures where moderate strength and high ductility are desired. The

optimum formulation appears to be approximately 0.5% xanthan gum, 6% starch, and 0.5% fiber, as higher fiber contents did not yield additional statistically significant benefits. However, this study was limited to a single sand type (poorly graded, SP) and room-temperature air curing. The long-term durability of the cross-linked biopolymer binder under wet—dry cycles, freeze—thaw cycles, or biological degradation remains unknown. The slight variability in water content (± 5 g) and curing temperature (± 5°C) may also have introduced some experimental noise, although the replication and randomization design should have minimized systematic bias. Field trials are necessary to validate whether laboratory performance reflects real construction conditions, where mixing methods, compaction efforts, and environmental exposure differ.

4.5 Future research directions

Future studies should investigate the resistance of optimized biopolymer fiber mixtures to cyclic wetting—drying and temperature variations, as these weathering processes are known to degrade biopolymer gels [6, 11]. Quantify the carbon footprint and life-cycle cost of cross-linked biopolymer stabilization relative to cement for a full-scale project.

Other biopolymer pairs (e.g., agar + xanthan, gellan + starch) have been explored to identify even more efficient cross-linking systems. The experimental matrix was extended to fine-grained soils and higher confining pressures to assess the performance under more realistic stress states.

5. Conclusions

This study investigated the combined effects of cross-linked biopolymers (xanthan gum and starch) and fibers (jute and polypropylene) on the unconfined compressive strength (UCS) of sandy soil through laboratory testing. The following conclusions can be drawn:

5.1 Effects of biopolymer cross-linking

While xanthan gum enhances strength through gel formation, the addition of starch further improves performance by reducing shrinkage and maintaining structural integrity. Starch cross-linked with XG achieved over twice the compressive strength of XG alone.

5.2 Effect of biopolymers vs. fibers

Biopolymers primarily govern strength enhancement through hydrogen and electrostatic bonding during curing, whereas fibers primarily influence ductility and postfailure resistance. Increasing the biopolymer content enhances the strength to an optimal level; fibers mitigate this brittleness by interconnecting soil aggregates and providing internal tensile resistance.

5.3 Fiber type comparison

Jute fiber-reinforced samples achieved higher compressive strengths than polypropylene-reinforced samples did, but these differences were not statistically significant ($p = 0.891$ and $p = 0.074$,

respectively). However, polypropylene fibers provided 23.6% greater ductility (strain capacity) than jute fibers did, indicating that the trade-off between strength and ductility depends on fiber selection.

5.4 Comparison with cement treatment

All the biopolymer- and fiber-treated samples, except XG and XGJ, exceeded the strength and strain capacity of the cement-treated sand. Notably, xanthan gum alone achieved higher tensile resistance than the cement-treated sample did; it remained highly brittle even after 28 days of curing.

5.5 Statistical validation of factor significance

ANOVA confirmed that starch content ($p < 0.001$), xanthan gum content ($p < 0.01$), and the interaction between biopolymer type and fiber content ($p < 0.05$) significantly influence UCS.

5.6 Study limitations and future work

The current study involved eight different combinations of soil, biopolymer, and fiber; the results could be expanded with additional combinations and curing conditions for further investigation. Future research should also explore the long-term durability of optimized biopolymer–fiber mixtures under field conditions.

The authors believe that this study provides experimental evidence and a statistically validated framework to help engineers and agencies use biopolymers and fiber-treated cohesionless soil as a sustainable alternative to cement stabilization.

Declarations

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Author contributions

Eisteuck Ahmed: Writing – original draft, Writing – review and editing, Investigation, Formal analysis, Data curation, Funding acquisition, Visualization, Software, Methodology. Mst. Mitu Khatun: Methodology, funding acquisition, conceptualization, software, and data curation. BM Mustasim Billah: Methodology, Investigation, Data curation. Md. Asif Hossin: Data curation.

Declaration of competing interests

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.

Data availability

The data set analyzed in the current study is available in Ahmed, Eisteuck (2025), “Unconfined compression tests data sets”, Mendeley Data, V1, doi: 10.17632/9bf7b4mdcp.1, and is licensed under a CC BY 4.0

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Figures

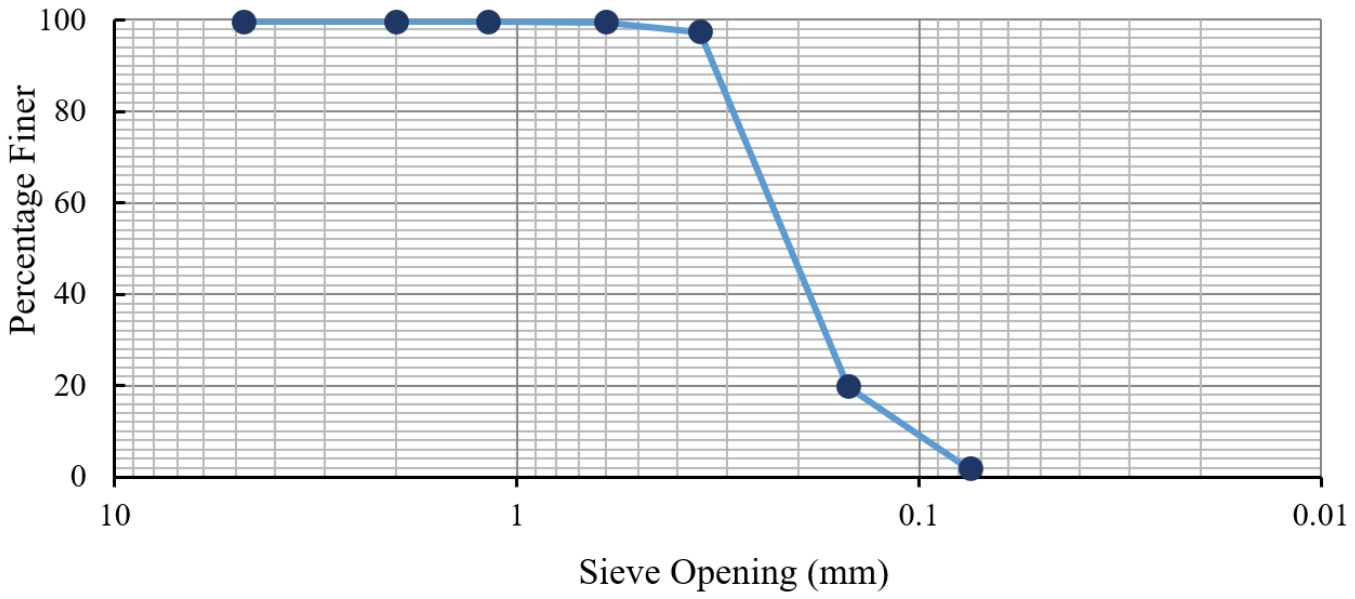


Figure 1

Grain size distribution curve for the sand substrate retrieved from the Balu River, showing the percentage of material finer than each sieve size.

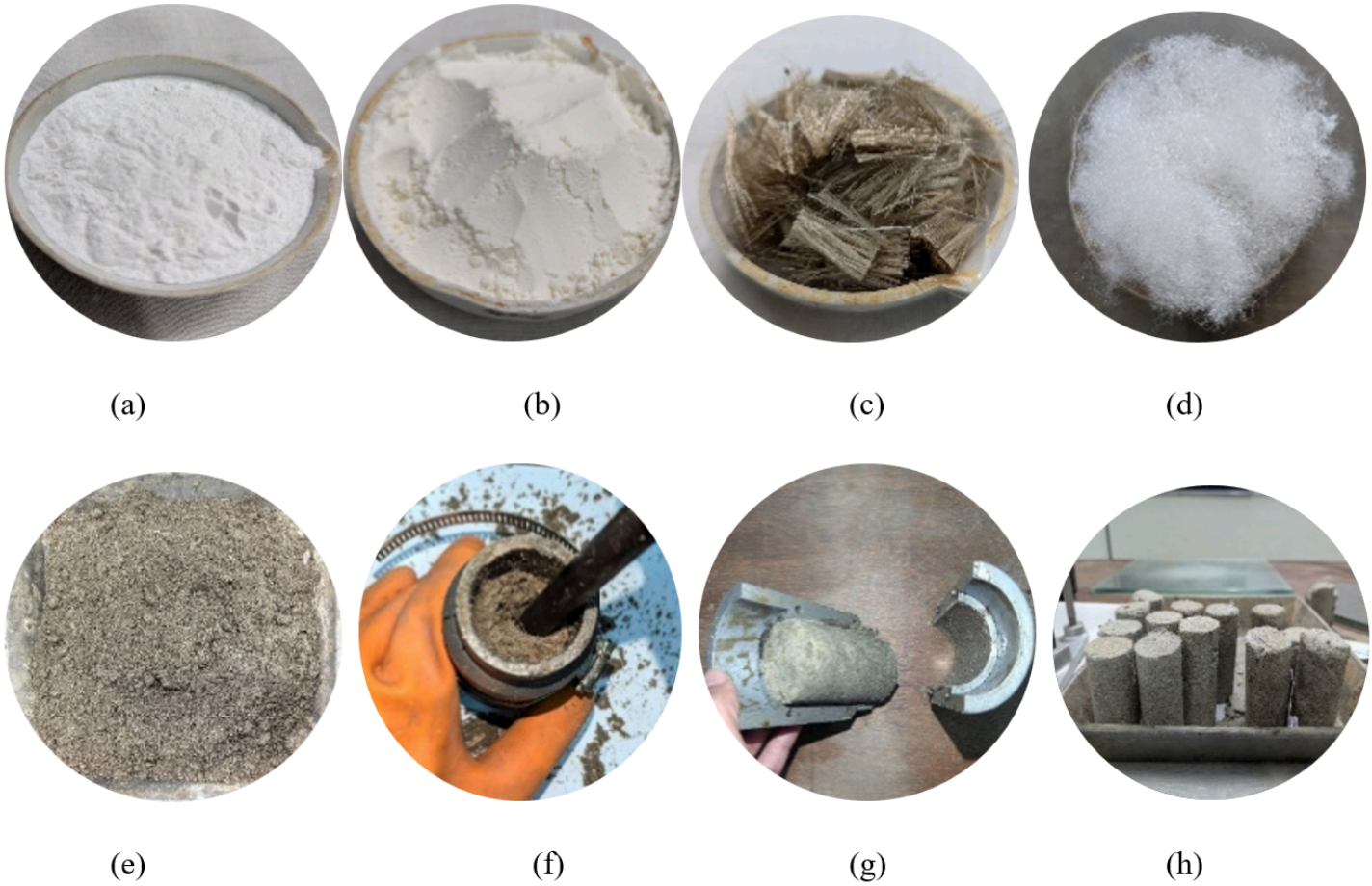
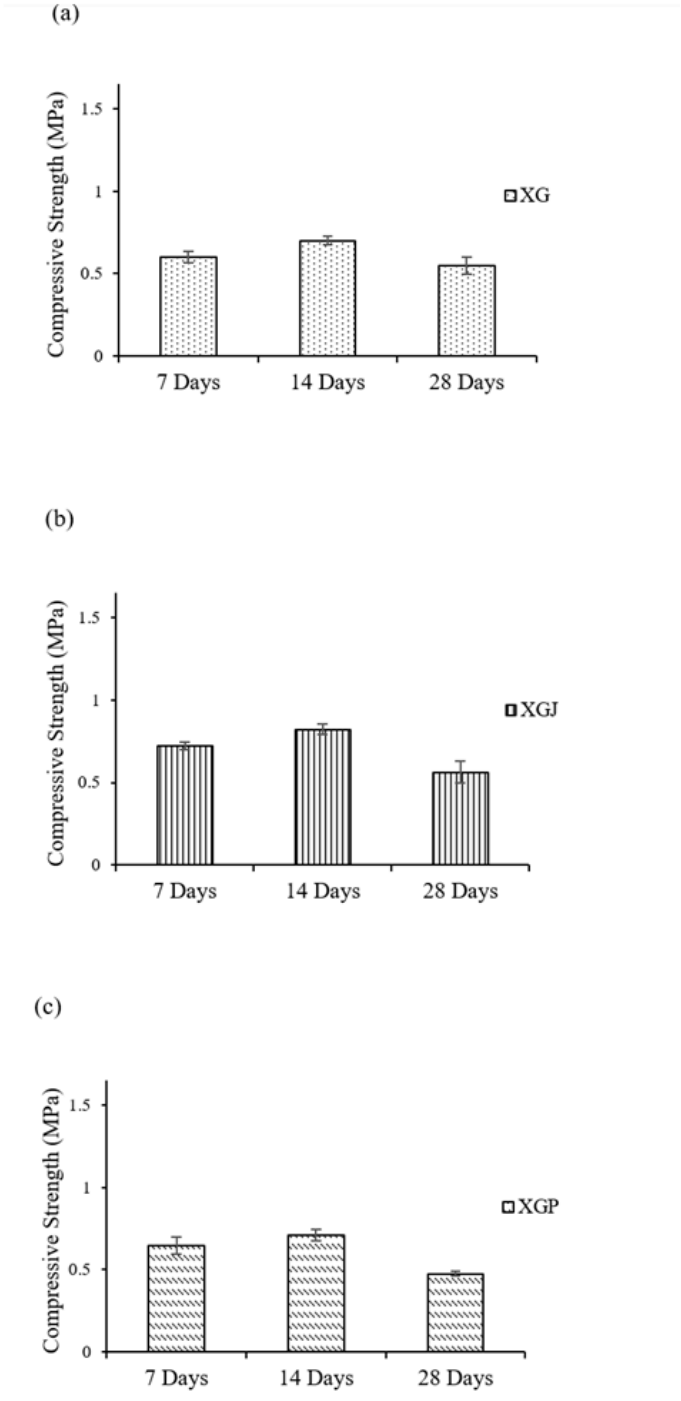


Figure 2

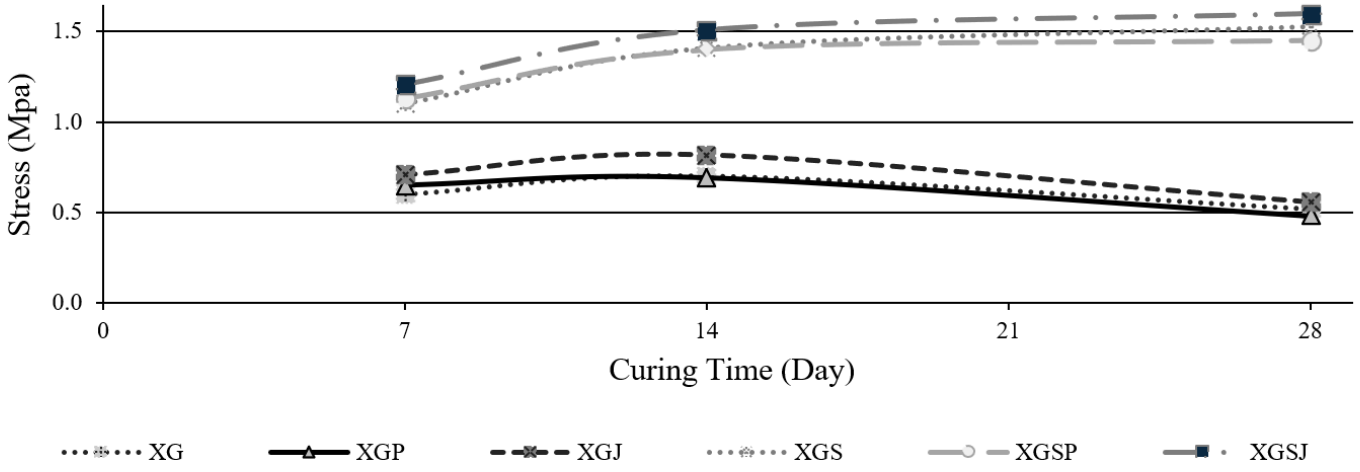
Visual representation of the samplepreparation: (a) Xanthan gum powder, (b) starch powder, (c) jute fiber, (d) polypropylene fiber, (e) soil biopolymer and jute fiber mixture, (f) mixture in the mold, (g) removal of the samplefrom the mold, and (h) air curing of the sample



The treated samples were tested at 7, 14, and 28 days of age.

Figure 3

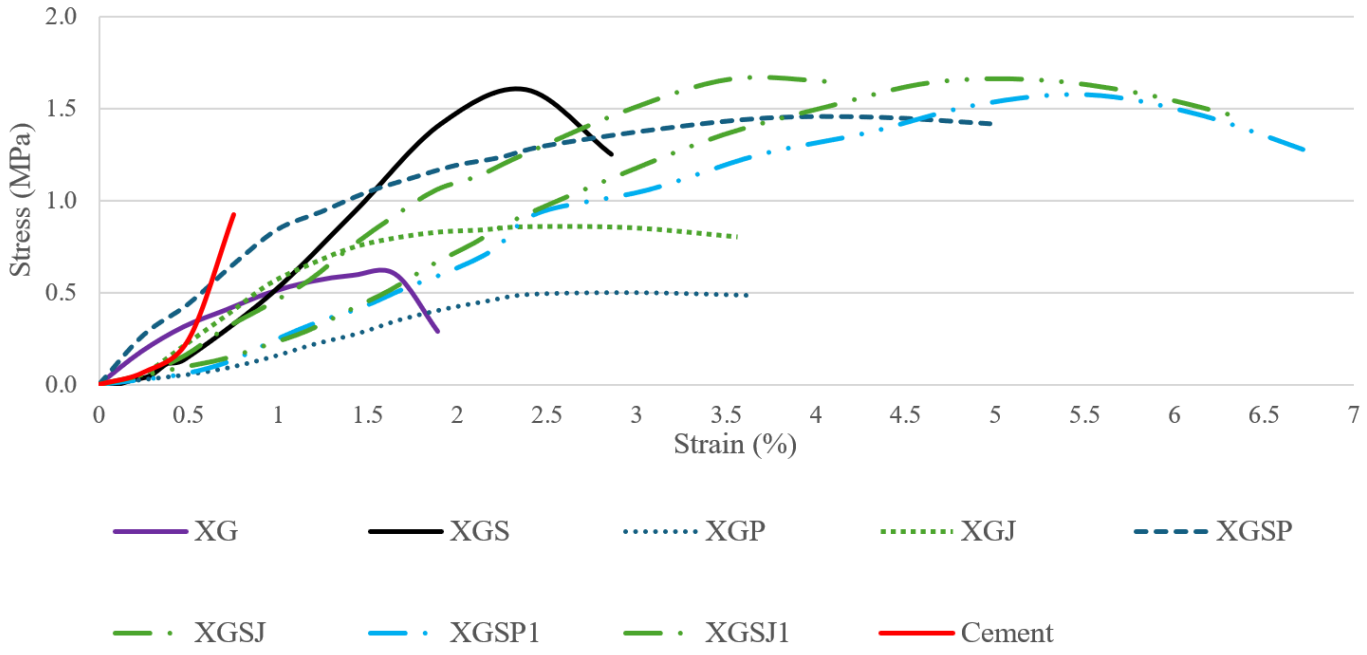
Variation in the unconfined compressive strength (MPa) with increasing curing time (7, 14, and 28 days) for different biopolymer fiber mixtures. Error bars represent ± standard deviation (n = 3), (a) XG (b) XGJ (c) XGP



The treated samples were tested at 7, 14, and 28 days of age.

Figure 4

Variation in unconfined compressive strength (MPa) with curing time (7, 14, and 28 days) for sand treated with cross-linked biopolymers (xanthan gum and starch) reinforced with fibers.



The treated samples were tested at 7, 14, and 28 days of age.

Figure 5

Stress–strain behavior of sand samples treated with different biopolymer–fiber mixtures after 28 days of air curing. The curves illustrate the variation in compressive stress with axial strain, highlighting differences in stiffness and ductility among the treatments.



(a)



(b)

Figure 6

Visual evidence of crack-bridging behavior in polypropylene fiber-reinforced sand (XGP sample), demonstrating resistance to crack initiation and propagation.