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Compaction and Permeability Characteristics of Biopolymer-Treated Sand

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Abstract

Traditional soil stabilization materials often cause environmental issues, prompting researchers to explore alternative, eco-friendly options such as biopolymers. This study examines compaction characteristics and permeability coefficient of poorly graded sandy soil treated with biopolymers, specifically Xanthan Gum (XG) and Guar Gum (GG), as sustainable substitutes for conventional stabilizers such as cement. The biopolymers were mixed with the soil in contents of 0%, 0.5%, 1%, 1.5%, 2%, 3%, and 4% of the dry weight of the soil. Furthermore, mixtures of both biopolymers were used, including 3% XG + 1% GG, 1% XG + 3% GG, 2% XG + 2% GG, and 1.5% XG + 1.5% GG, based on the dry soil weight. The study involved a series of experiments to evaluate the impact of different biopolymer contents on two key geotechnical properties of soil, compaction characteristics and permeability coefficient (k). Adding XG increased the maximum dry density (MDD) to 1.87 g/cm³ at 1% concentration, while GG peaked at 1.93 g/cm³ at 2%. Both biopolymers significantly reduced permeability, with GG being more effective due to its higher viscosity, enhancing particle bonding and pore blockage. Findings revealed that biopolymers significantly enhance compaction characteristics and reduce permeability of the soil. Based on the findings of this study, it is recommended to utilize XG and GG as effective agents for soil stabilization in dry conditions.

Keywords: Biopolymer-treated sand; compaction characteristics; soil permeability; Xanthan Gum; Guar Gum; environmentally sustainable stabilizer.

Introduction

There are numerous techniques for stabilizing the soil, including the use of physical, mechanical, and chemical methods. In many engineering applications, relying solely on mechanical or physical methods is not feasible, as the circumstances often require the use of admixtures to improve the soil's engineering properties to desired levels. Natural admixtures, such as straw, are less effective compared to cement [1]. When evaluating the environmental effects of chemical stabilization methods, research should focus on both the impact of the chemical after it is applied and the processes involved in its production. Examining the effects of cement-based soil stabilization first highlights the environmental impact during cement production. Additionally, the matrix stabilization that inhibits vegetation growth on topsoil shows that cement stabilization is not an eco-friendly technology. The widespread use of cement leads to numerous environmental issues, including increased runoff, air pollution, and the creation of heat islands. Furthermore, it is challenging to restore cement-treated soil to its original condition [2].

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Biopolymers are eco-friendly polymers produced by living organisms, and they have diverse applications across various fields, including agriculture, biomedical engineering, food processing, the chemical industry, the energy sector, and environmental protection and remediation. Biopolymers commonly used for soil modification include guar gum, xanthan gum, chitosan, and sodium alginate. Toxicity studies conducted by the World Health Organization in 1975 and 1987 concluded that guar gum and xanthan gum pose no health risks, eliminating the need to define an acceptable daily intake for these substances. With these considerations, biopolymer-based soil modification is regarded as an environmentally sustainable technology [1].

Several studies have examined how biopolymers affect the geotechnical behavior of clay soils. Bozyigit et al. [3] evaluated kaolinite treated with xanthan gum and guar gum at various moisture levels. They observed that the unconfined compressive strength (UCS) of all biopolymer-amended samples increased over a 90-day curing period, with the greatest gain at 25% water content and 2% xanthan gum after 90 days. Ni et al. [4] showed that the UCS of xanthan-gum-treated Shanghai clay rose as initial moisture content increased, identifying an optimal moisture level that maximized strengthening efficiency. Research by Amiri Tasuji [5] showed that applying chitosan biopolymer to sand lowers its permeability, with greater chitosan dosages producing even less permeability. Using chitosan as a surface coating was found to be far more effective at blocking water ingress than blending it into the soil. Triaxial test results further revealed that chitosan increases soil cohesion while slightly reducing the internal friction angle, leading to a net gain in shear strength.

On the other hand, some researchers [6-8] have investigated the effects of biopolymers on permeability and compaction characteristics of sandy soil. For example, Wiszniewski and Firat [6] reported that soil-biopolymer mixture has less permeability than the natural ones. Optimum moisture content (OMC) and maximum dry density (MDD) are critical parameters when utilizing soil in engineering applications. Soil treated with biopolymers exhibits a higher MDD compared to untreated soil, while the change in OMC is minimal [7]. Reddy and Varaprasad [8] showed that incorporating biopolymers into soil results in a decrease in MDD and an increase in OMC.

This study is aligned with the Sustainable Development Goals (SDGs), specifically SDG 15: Life on Land, which focuses on the protection, restoration, and sustainable management of terrestrial ecosystems. By employing eco-friendly biopolymers for soil stabilization, this research addresses the pressing challenges of land degradation and soil erosion, thereby fostering healthier ecosystems. Additionally, the use of biopolymers not only improves soil stability but also minimizes dependence on chemical additives, which corresponds with SDG 12: Responsible Consumption and Production. Moreover, by advocating for the use of sustainable materials, this research contributes to SDG 13: Climate Action, as maintaining healthy soils is essential for carbon sequestration and reducing the impacts of climate change [9].

The objective of this research is to experimentally evaluate the compaction and permeability characteristics of sandy soil treated with biopolymers. This study aims to assess the effectiveness of xanthan gum (XG) and guar gum (GG) in stabilizing poorly graded soil, highlighting their environmentally friendly properties and natural origins. While many previous studies have investigated the effects of each biopolymer individually, there has been limited focus on the combined effects of two types of biopolymers on sandy soil properties. Therefore, this study addresses this gap.

Materials and Methods

Natural sand was obtained from borrow pits in New Aswan City, Aswan, Egypt, at a depth of 3.0 meters. The samples were thoroughly mixed, placed in plastic bags, sealed tightly, and packed into cardboard boxes. Soil aggregates were carefully crushed with a pestle and mortar to speed up the drying process. After grinding, the soil was sieved through a number 4 mesh and stored in plastic containers. The soil consists of 6% coarse sand, 86% medium sand and 8% fine sand. The particle size distribution curve is presented in Fig. 1. According to the Unified Soil Classification System (USCS), the soil is classified as poorly graded sand (SP), where C_u (coefficient of uniformity) = 0.21 and C_c (coefficient of gradation) =2.04.

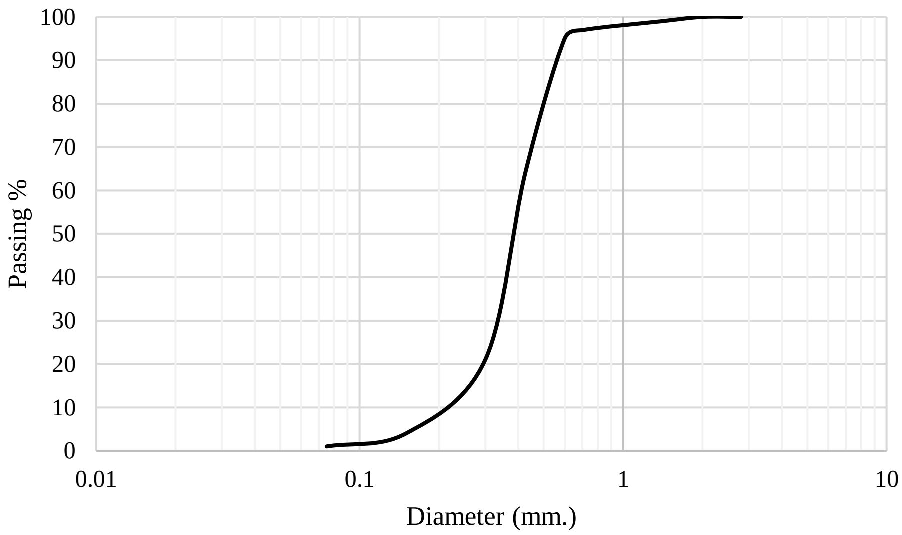

Fig. 1 The particle size distribution curve of the soil

Two biopolymers, XG and GG, were chosen for their cost-effectiveness relative to other biopolymers. Thong Sheng Food Technology Sdn Bhd produces them in Penang, Malaysia [10]. The physical and chemical properties of biopolymers used in this study are presented in Table 1 [3].

Table 1: Physical and chemical properties of biopolymers [3]

Type	Form	Molecular weight (g/mol)	pH	Viscosity (mPa.s)
XG	Powder	241.2	8.3	1551
GG	Powder	535.15	6.4	5750

A specific proportion of biopolymer powder, by mass, was thoroughly blended with the soil. The biopolymer content is calculated by dividing the mass of the biopolymer powder by the dry mass of the soil and expressing it as a percentage. In this study, the chosen biopolymer contents were 0%, 0.5%, 1%, 2%, 3%, and 4%. Additionally, mixtures of both biopolymers were used, including 3% XG + 1% GG, 1% XG + 3% GG, 2% XG + 2% GG, and 1.5% XG + 1.5% GG, based on the dry soil weight. Table 2 summarizes the testing program for this study. Subsequently, distilled water at 13.0%, identified as the optimum moisture content (OMC), was added to the soil-biopolymer mixture and mixed until a uniform consistency was achieved. All soil samples, both untreated and biopolymer-treated, were compacted to their maximum dry density (MDD) and optimum moisture content (OMC). After compaction, the treated soil samples were kept at a temperature of (45°C).

Table 2: Summary of testing program

Biopolymer type	Biopolymer content (%)	Mixing method
XG	0%, 0.5%, 1%, 2%, 3%, and 4%	Dry mixing
GG	0%, 0.5%, 1%, 2%, 3%, and 4%	Dry mixing
Combination of XG and GG	• 3% XG + 1% GG • 1% XG + 3% GG • 2% XG + 2% GG • 1.5% XG + 1.5% GG	Dry mixing

The modified Proctor test was conducted to measure the OMC and MDD of the natural soil in accordance with ASTM D1557 − 12´1. A constant head test was performed to assess the k of the natural sand. To determine the k of biopolymer-treated soil samples, falling head tests were conducted using a cylindrical mold with a diameter of 10.16 cm, following ASTM D- 2434 standards at room temperature (25°C). The biopolymer-treated soil samples, at their maximum dry density (MDD) and with a 13% water content, were compacted into five layers within the compaction mold. After extrusion from the mold, the soil samples were trimmed to a standard size. Each concentration was tested three times to ensure accuracy. Fig. 2 shows a flowchart for research methodology.

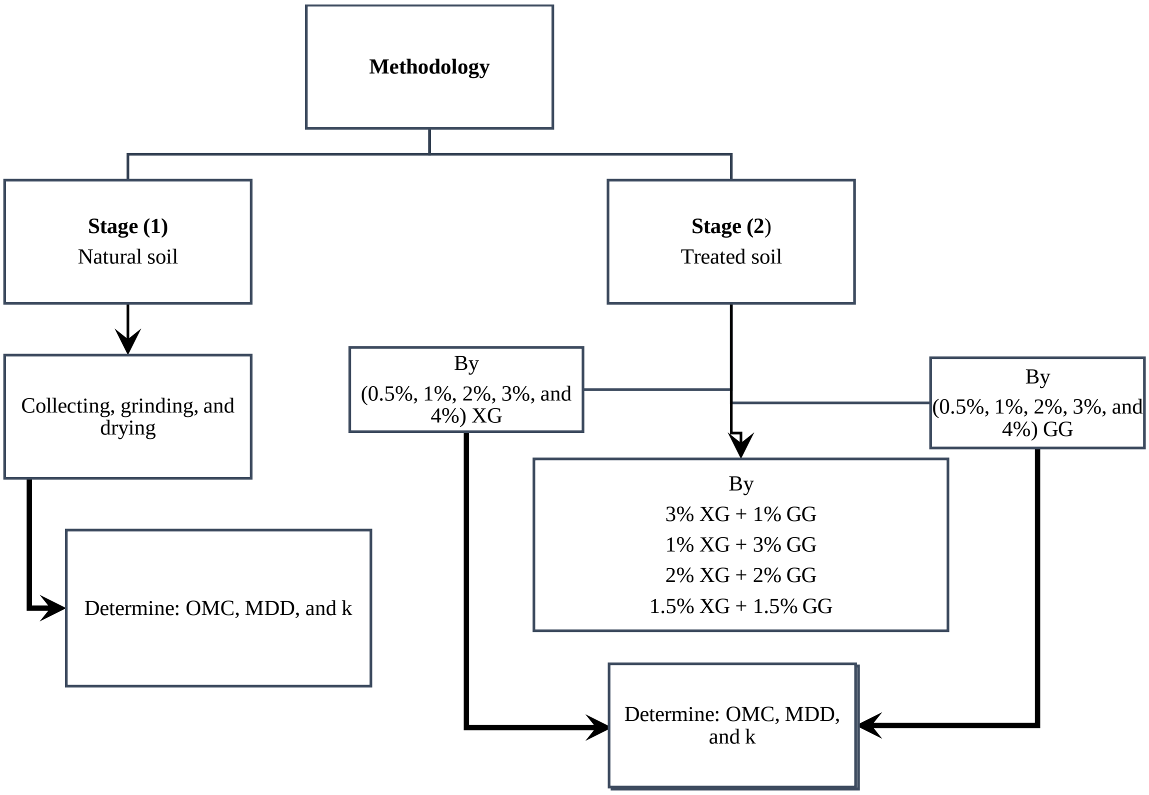

Fig. 2 A flowchart indicating research methodology

Results and discussion

Effect of biopolymers on compaction characteristics of soil

When carrying out the modified Proctor test on the natural soil, the MDD was recorded to be 1.79 g/cm³, with an OMC of 13%, as illustrated in Fig. 3. The MDD and OMC values for both natural and biopolymer-treated soil are shown in Figs. 4 and 5, respectively. The MDD progressively rose with the addition of XG. At a content of 0.5% XG, the MDD increased to 1.82 g/cm³, and at 1%, it reached 1.87 g/cm³. This upward trend in MDD continued with higher XG content until a peak was observed at 3%, beyond which the MDD began to decline. On the other hand, the OMC showed a gradual increase, rising from 13% for natural soil to 13.2% with the addition of 0.5% XG, and further reaching 14.4% at a 4% XG content. Similarly, the addition of GG to the soil resulted in a significant increase in the MDD. At a 0.5% content of GG, the MDD reached 1.83 g/cm³. Increasing the GG content to 2% further elevated the MDD to 1.93 g/cm³. However, at a 3% content, the MDD began to decrease, reaching 1.85 g/cm³. This decline continued with a 4% content of GG, reducing the MDD to 1.78 g/cm³. The results also indicated a more gradual rise in OMC, which reached 14.95% at a 4% content of GG.

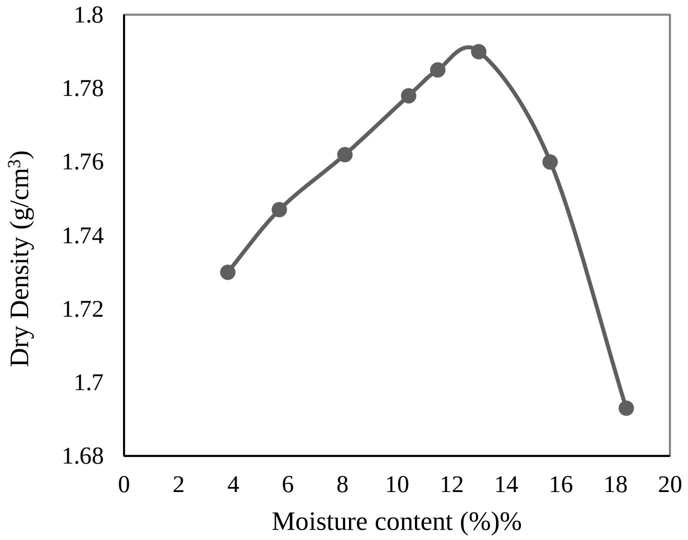

Fig. 3 Compaction curve of the natural soil showing MDD at 1.79 g/cm³ and OMC at 13%

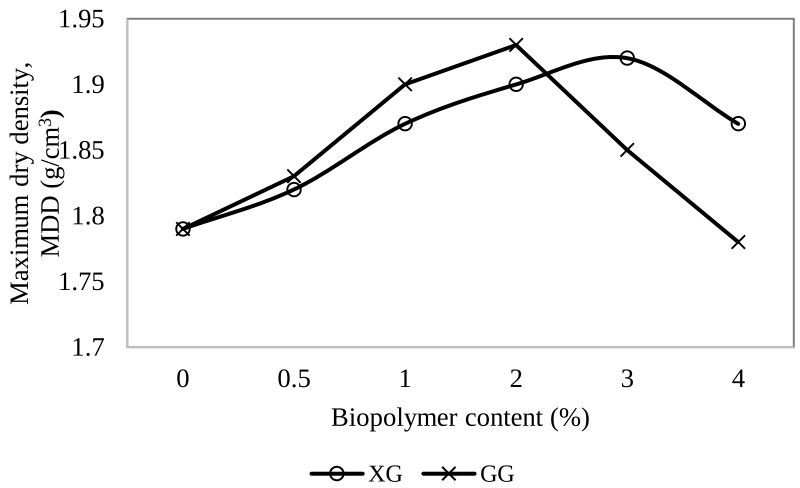

Fig. 4 The maximum dry density of biopolymer-treated soil

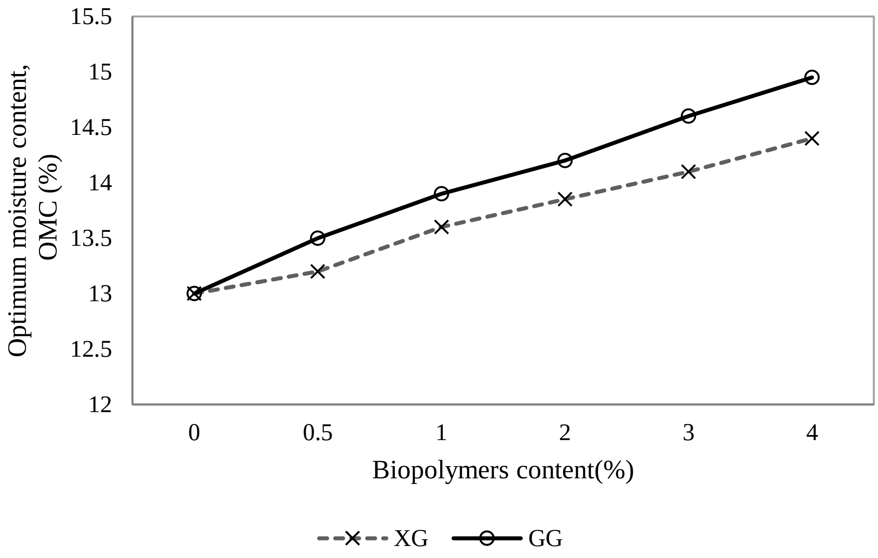

Fig. 5 The optimum moisture content of biopolymer-treated soil

The increase in MDD can be attributed to the strong interaction between biopolymers and water molecules, as biopolymers are hydrophilic [11-13]. This interaction leads to the formation of gel biofilms that coat sand grains [14], facilitating better packing during the compaction process. This improved packing reduces friction between the grains and utilizes part of the water content for the partial hydration of the biopolymer. Our findings align with the results of [15-17]. They indicated that soil treated with XG shows a gradual increase in MDD compared to the untreated soil, accompanied by a slight decrease in OMC.

The reduction in MDD can be attributed to the physical properties of biopolymers, specifically the viscosity of their solutions [18]. As the content of biopolymer increases, so does the solution's viscosity, resulting in a decrease in MDD, specifically for XG [2,13]. In contrast, the same concentrations of GG result in even higher viscosity [19-21], which further decreases MDD due to the separation of soil particles caused by the high viscosity, leading to a dispersion of compaction energy [2]. Other studies [15,22,23] noted that the addition of either type of biopolymer increases the MDD and the optimal water content up to a certain biopolymer content. Beyond this content, the MDD decreased as the OMC continued to rise. This phenomenon occurs because a small percentage of biopolymer lubricates the soil grains, increasing the MDD and necessitating more water for the hydrogenation process, which forms a hydrogel network [24]. However, as the biopolymer content increases, the solution's viscosity also increases, leading to more condensation, branching, and interconnection of the three-dimensional hydrogel network. This distribution and dispersion of compaction energy resulted in a decrease in MDD and a further increase in the OMC required to absorb water for the formation of the hydrogel network at higher contents [12].

In this study, when 3% GG was added, the MDD decreased, whereas the same percentage of XG increased the MDD. This can be explained by the fact that the high molecular weight increases the locations of chemical bonds including covalent bonds between the parent chain and sub-chains of one monomer, and hydrogenation between the polar water molecules [19,20]. This causes the GG to occupy more space, hindering the rearrangement of soil particles to achieve greater density. Additionally, the rapid formation of the hydrogel matrix prevents an increase in density due to its lower density relative to soil grains [12,14,25]. In contrast, XG, with a relatively lower molecular weight, forms a hydrogel that acts as a coating around the soil particles, allowing them to slide and rearrange more densely during compaction [2,15]. This results in less clumping compared to GG, providing more space for soil grains to agglomerate tightly [26].

When both biopolymers were combined in different proportions, it was observed that the MDD, which decreased with 3% GG (1.85 g/cm³), improved somewhat with 1% XG, along with a noticeable increase in OMC (Fig. 6). The MDD value was better with a combination of 1.5% GG and 1.5% XG. This is due to the interaction between GG and XG in solutions, where the D-mannose groups in both biopolymers interact with acetyl groups, forming carboxyl and hydroxyl groups in higher proportions [13] thereby enhancing hydrogel production with better physical properties [27]. The galactose side chains of the gums are covalently linked within their molecules, forming hydrogen bonds with other chains and glucuronic acid in xanthan, creating a stronger hydrogel network [13,27]. The increase in OMC with GG is due to its higher water demand for hydrogel formation, attributed to increased reaction sites and chain length from higher molecular weight. XG requires relatively less water [28], hence higher content of GG corresponds to higher OMC values.

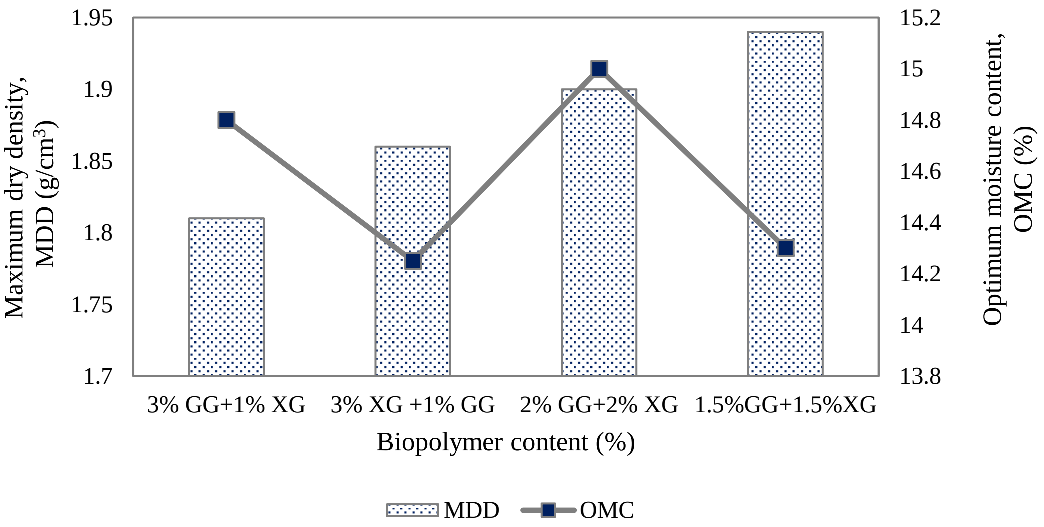

Fig. 6 Compaction characteristics of (XG+GG)-treated soil

Effect of biopolymers on permeability coefficient of soil (k)

The values of natural and biopolymer-treated soil are presented in Fig. 7. The k of untreated soil was 3.2 × 10^{-2} cm/s. When the soil was treated with 1% XG, the k decreased by 45% (1.76 × 10^{-2} cm/s). Similarly, treating the soil with 1% GG resulted in a 55% reduction in permeability (1.44× 10^{-2} cm/s). The most significant decrease in the k occurred at a content of 4% for both biopolymers. At this point, the k decreased by 93% with XG (0.224 × 10^{-2} cm/s) and by 96% with GG (0.128 × 10^{-2} cm/s).

It was found that treating soil with GG results in a greater reduction in permeability compared to XG. This is due to the higher viscosity of the hydrogel formed when GG dissolves in water, even at low concentrations [25]. One of the most significant properties of GG is its ability to create a high-viscosity hydrogel upon rehydration in cold water systems. At the same content, both GG and XG can be considered effective in enhancing soil suction and resistance to internal flow [29].

The reduction in permeability can be attributed to the presence of connecting elements between soil particles and those within soil voids, known as pore-clogging [1,15]. This phenomenon impedes the flow through the treated soil. Notably, increasing the concentration of the biopolymer enhances both the quantity and strength of these bonds [18,27,30]. Previous studies have highlighted that the stabilization effect of biopolymers in soil is due to the creation of bonds between soil particles and the filling of voids with hydrogels [14,30]. The XG and GG, being hydrocolloids, can absorb and retain water by forming hydrogel matrices [13,19]. These hydrogels consist of a three-dimensional network formed by the interaction of water molecules with long interconnected chains of XG and GG, which traps water within their matrix and enhances the soil's water retention capacity for hydration and the formation of network branches [31]. The permeability decreases because the biopolymer matrix shrinks within soil gaps during drought. Therefore, soil permeability was measured after 30 days to ensure drought conditions were fully realized [32].

It was observed that treating the soil with 2% XG and 2% GG resulted in k values of (0.16×10^{-2} cm/s). A similar k was observed with a mixture of 1.5% XG and 1.5% GG, as illustrated in Fig. 8. When the soil was treated with a mixture of 1% XG and 3% GG, the k was measured at (0.192×10^{-2} cm/s), which closely approximates the k of soil treated with 4% XG alone. This outcome is attributed to the fact that a higher concentration of GG creates a denser hydrogel network compared to the network formed by the same proportion of XG [16].

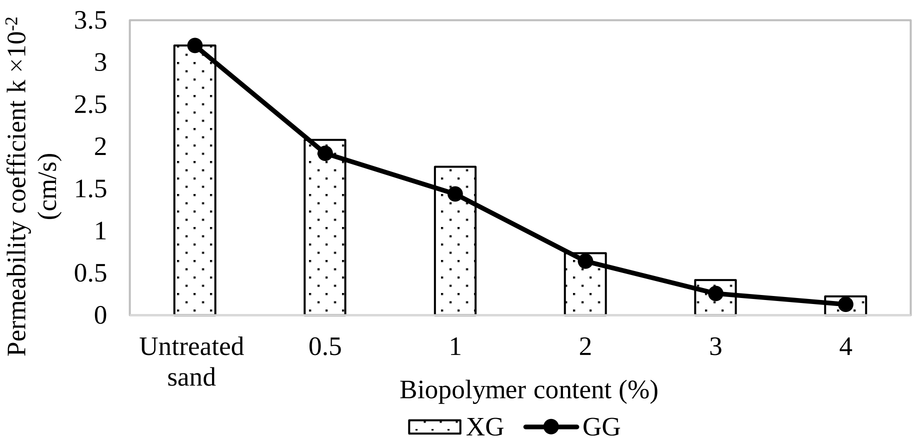

Fig. 7 Permeability coefficients of untreated and biopolymer-treated soil

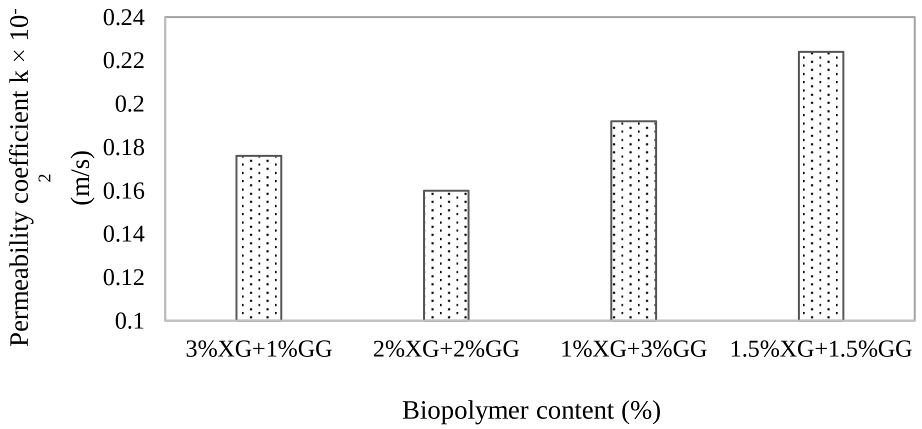

Fig. 8 Permeability coefficients of (XG+GG)-treated soil

Limitations and comparison

The biopolymers were mixed as a powder with the soil in a dry blend, and then water was added. The mixing method may affect the results; therefore, it is necessary to study the impact of water content on the soil properties.

Table 3 presents the compaction characteristics from different research. The results demonstrate increases in both OMC and MDD upon treatment. Table 4 compares the results of permeability from previous studies. It was observed that the treatment of the soil by biopolymers significantly reduced the permeability of soil.

Table 3: Summary of compaction results from previous studies

Type of soil	Biopolymer	OMC (%)		MDD (kN/m^3)		Reference
		Untreated soil	Treated soil	Untreated soil	Treated soil	
Poor-graded sand	2% XG	12	14.5	19.1	20.2	[33]
Clayey sand	4% XG	14.5	15	18.2	17.3	[24]
Clayey sand	2% XG	21	23	16.4	15.4	[35]
Poor-graded sand	2% GG	12.4	15.3	18.98	17.12	[34]
Clayey sand	2% GG	21	27	16.4	14	[35]
Clayey sand	2% GG	14.5	15.8	18.2	17.8	[24]
Silty sand	2% GG	10.5	13.7	21.2	19.1	[36]
Silty sand	0.5% XG	10.5	12.4	21.2	20.1	[36]
Poor-graded sand	0.9% XG	7.25	7.95	18.8	19.8	[37]
Clayey sand	1% XG	14.15	15.44	18.4	18.1	[38]
Poor-graded sand	0.5% GG	12	15	19.1	20.2	[33]
Silty sand	1% XG	10.2	10.4	19	19.4	[39]

Table 4: Summary of permeability results from previous studies

Type of soil	Biopolymer	Permeability (cm/s)		Curing period	Reference
		Untreated soil	Treated soil		
Sandy clay	0.25% XG	1×10^{-3}	8.5×10^{-7}	7 days	[34]
Poor-graded sand	0.5% XG	8.46×10^{-5}	8.56×10^{-10}	1 day	[40]
Silty Sand	0.5% XG	1×10^{-4}	0.5×10^{-11}	7 days	[36]
Poor-graded sand	1.25% XG	2×10−4	2×10^{-6}	Post-sampling	[41]
Poor-graded sand	1% XG	8.43×10^{-3}	5×10^{-8}	7 days	[42]
Poor-graded sand	0.5% GG	1×10^{-3}	1.46×10^{-7}	3 days	[43]
Silty Sand	2% GG	1×10^{-4}	0.5×10^{-8}	7 days	[36]
Poor-graded sand	2% GG	3.4×10^{-2}	0.1×10^{-2}	35 days	[33]

Conclusions

This research investigated the effect of adding XG and GG as sustainable biopolymers in soil stabilization, offering environmentally friendly alternatives to traditional stabilizers such as cement. Laboratory tests were carried out to determine the compaction characteristics and permeability of biopolymer-treated sand. The results revealed that adding XG increased the MDD, peaking at 1.87 g/cm^3 at a 1% concentration, while the OMC rose to 14.4% at a 4% XG concentration. Similarly, GG enhanced the MDD to 1.93 g/cm^3 at 2%, however, it decreased at higher concentrations, with the OMC reaching 15% at 4% GG. This is due to the strong interactions between biopolymers and water resulting from their hydrophilic nature. These interactions create gel biofilms that enhance packing and reduce friction among sand grains, leading to an increase in MDD, particularly with XG. However, as biopolymer content increases, the viscosity of the solution also rises, which can lead to a reduction in MDD due to particle separation and dispersion of compaction energy. Furthermore, the study demonstrates that applying biopolymers to soil significantly decreases its permeability, with 4% GG achieving a 96% reduction (to 0.00128 cm/s) and 4% XG resulting in a 93% reduction (to 0.00224 cm/s). GG proves to be more effective than XG because it forms a higher-viscosity hydrogel, which strengthens the bonding between soil particles and blocks pores. This reduction in permeability is mainly due to the development of a hydrogel matrix that fills the gaps in the soil and restricts water movement, especially during drought conditions.

Recommendations

Subsequent investigations could pursue the following avenues:

- **Evaluating an expanded array of biopolymers** across diverse environmental settings to pinpoint the most effective soil-stabilizing agents for specific applications.
- **Conducting long-term field trials** to determine the durability and performance of biopolymer treatments over time, thereby clarifying their influence on soil properties.
- **Performing comparative analyses** between biopolymer-based approaches and conventional chemical stabilizers to generate data on relative performance, cost-effectiveness and environmental impact.
- **Developing practical application guidelines** for using biopolymers in various soil types and conditions, thus equipping practitioners with clear, field-ready protocols.

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Conflict of interest

The authors declare that they have no conflict of interest.

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