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Effect of Xanthan gum biopolymer combined with fibre as soil- stabilization binder of dune sand in Southern Algeria

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Abstract. Biopolymer treatment of geomaterials is a promising technology with green technology potential that can help reduce global warming. It offers a positive environmental impact and a wide range of applications. This paper reports the results of a study of the mechanical performance of biopolymer-treated dune-sand from the Algeria desert. The sand was mixed with varying amounts of xanthan gum biopolymer and reinforced with polypropylene fibre. The study demonstrated that xanthan gum treatment improved the Unconfined Compressive Strength (UCS) of unreinforced sand and fibre-reinforced sand. Nonetheless, the test results revealed that biopolymer-treated sand manifested higher resistance after drying. Based on the findings, the optimal quantity of xanthan gum for treating sand is 2%. The incorporation of fibre in the matrix increases the strength and failure strain. The Scanning Electron Microscopy (SEM) analysis further substantiated that the biopolymer bonds the sand particles together and the distribution of PP fibre in the mixture, thereby enhancing compressive strength and durability. The results indicate that using xanthan gum biopolymer treatment offers an environmentally friendly approach to enhancing the mechanical properties of desert sand.

Keywords: biopolymer; compressive strength; desert sand; polypropylene fibre; SEM test; Xanthan gum

1. Introduction

Biopolymers are considered as an effective solution for the improvement of the engineering properties of soils (Chang 2010, Taytak *et al*. 2012, Khatami and O'Kelly 2013, Ayeldeen *et al.* 2016, Cho *et al.* 2021), Biopolymers are enzymes of bio-cementation molding their macro-molecules onto soil particles thereby creating covalent links to form a solid structure in soils. In recent decades the research on the potential of biopolymers for soil improvement has become a tremendous way of interest. As an eco-friendly material rather than cement for reducing carbon dioxide (CO_2) emissions (Bagheri *et al.* 2023), it will be a better safeguard for our environment than other chemical stabilization processes. It is also inexpensive in that it can be used efficiently for engineering projects. Instead, their performance of sustainability has significantly influenced some factors such as the biopolymer type effect, concentration, curing time, loading rate, and other parameters. Soils mixed with biopolymers of high viscosity improves the strength, including increased cohesion, resistance to erosion, reduced permeability and alike, by serving as a binder. The direct usage of biopolymers in soils has various benefits over pre-existing biological soil remediation methods (Cole *et al.* 2012, Chang *et al*. 2016). Several researches have shown the benefits of the biopolymer effect on soil behaviour and their improvement of soil sustainability against collapse. Soil stabilization and reinforcing techniques have been the focus of significant research in geotechnical engineering to improve the mechanical properties of soils. These developments are necessary for applications varying from road construction to slope stability and foundation design (Chang *et al.* 2016, 2020, Lee *et al*. 2017). Among a number of techniques studied, the use of additives and fibres to enhance soil performance has attracted significant interest due to the results achieved and cost-efficiency (Lee *et al*. 2019, Liu *et al*. 2017, Chang and Al-Sadarani 2017).

Latifi *et al.* (2017) investigated the effect of curing time and biopolymer concentration on the shear strength of xanthan-gum-modified organic peat. The curing periods were 3, 7, 28, and 90 days, with biopolymer concentrations

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of 0.5%, 1.0%, 1.5%, and 2.0%. The cohesion and friction angle increased significantly with increase in curing time during the first 28 days at an optimum concentration of 2%. Qureshi *et al*. (2017) examined the UCS and unconsolidated undrained (UU) shear strength of sand modified with xanthan gum (concentrations of 0%, 1%, 2%, 3%, and 5%) at confining pressures of 50, 100, and 150 kPa. This study reported an optimal concentration of 2% to achieve maximum increases in the UCS. However, strength decreased at higher concentrations. Another reported by (Soldo *et al*. 2020),), The authors have performed a series of UCS, direct shear (DS), and UU triaxial tests on residual piedmont soil treated by five different types of biopolymers in various biopolymer concentrations (1%, 2%, and 4%), and different curing times. Their study has shown promising results for soil stabilization and provided enormous potential for future sustainable engineering. In addition (Soldo *et al.* 2021) studied the influence of biopolymers on the strain localization on both silty and sandy soils, using a significant increase in soil resistance obtained with the increase of biopolymer content. Recently, (Boukeffoussa *et al,* 2023) investigated the effect of xanthan gum biopolymer on the shear strength of sand; for a concentration of xanthan gum varying between 0.25 to 1%, their results showed that a significant improvement in mechanical characteristics of sand by adding xanthan gum, they also recommended the utilization of xanthan gum for the long term efficiency of sand reinforcement. Recently, studies of the combined effect of fibre mixed with polymers extensively focused on the investigation of the mechanical behaviour of clay and sandy soil. (Ma *et al*. 2022) evaluated the effects of polymer content, fibre content, and dry density on the UCS and direct tensile strength (DTS) of the polymer-treated fibre-sand composite. The results showed that a considerable increase was obtained in both the UCS and DTS of the reinforced sand with the increase of polymer content, fibre content, and dry density. In addition, the results indicated that the polymer content had a better performance in increasing the peak stress, especially for soils with high dry density.

An interesting finding is that the fibre content is more effective on post-peak stress. It is also noticed that the use of both polymers and fibres in soil reinforcement effectively prevents the propagation and development of cracks under applied stresses. From SEM images, the results of the study showed that the surface coating, bonding, and filling effects caused by the polymer matrix greatly enhanced the interfacial interactions, thus providing a cohesive environment in which the strength of the fibres could be readily mobilized. The use of biopolymers in treated sand has been reported in the literature. Liang *et al*. (2022) investigated the influence mechanism of three types of fibres on the biocemented calcareous sand using the frozen-dried microorganisms on the UCS and DTS. Furthermore, calcium carbonate content was carried out to estimate the properties of cemented calcareous sand, the results of their tests indicate that biocemented calcareous sand reinforced with carbon fibre is more ductile, has a bridging function, and calcium carbonate content than basalt and glass fibres.

The Unconfined Compressive Strength (UCS), tensile strength, and calcium carbonate content of bio-cemented calcareous sand also increased proportionally with the addition of more fibre content. (Feng *et al*. 2023) reported that the potential of xanthan gum-treated silty sand mixed with jute fibre resulted in a better mechanical performance on UCS and DTS. Xanthan gum applications in soil stabilisation are valuable solutions for infrastructure, erosion control and land reclamation. The biopolymer's ability to bind sand particles and improve soil physical properties can significantly enhance the stability and usability of sandy soils, especially in arid regions, many studies where Xanthan gum has been successfully applied for stabilizing dune sand in infrastructure projects, erosion control systems, or desert greening initiatives. Due to its environmental benefits, such as biodegradability, low toxicity, and potential to improve soil health for vegetation growth, xanthan gum could be a viable soil stabilizer. Additionally, the cost-effectiveness of biopolymers compared to traditional chemical stabilizers, especially in terms of long-term sustainability, further supports the potential of xanthan gum as a soil stabilizer.

However, the research on the effect of physical properties of soil treated with biopolymer and mixed with fibre still needs to be completed and needs further documentation.

In their research, (Liu and Lyu 2023) indicates that polymer coatings can resist abrasion, while roughness values gradually approach those of natural sands. Further study of the surface characteristics of the particles shows more pronounced peaks and troughs at higher stress levels, suggesting significant height variations and notable diversity in the surface profiles. The use of probabilistic analysis techniques provides an opportunity to understand more precisely how particle surface properties evolve with increasing stress levels and their significant variations. This approach may be useful for studying the mechanical behaviour of coated sands, which is currently considered to be the most sensitive, their study highlights the importance of probabilistic approaches to understanding and predicting the behaviour of materials with changing properties, such as bio-cemented or fibre-reinforced soils. Similarly, (Liu *et al*. 2024) studied the effect of how polymer coatings affect the behavior of granular materials, using advanced copula-based probabilistic methods. They used log-normal distributions to measure critical stress ratios for natural sand, lightly coated (0.05%) sand, and heavily coated (3%) sand. While the critical stress ratios for natural and lightly coated sand were similar to those calculated using linear regression, the analysis for heavily coated sand showed a significant difference. They conclude that the critical stress ratios for the heavily coated sand revealed an interesting relationship with the stress level, indicating a complex interaction between material modification and stress response. Their research highlights the importance of using probabilistic analysis to understand materials with changing properties when subjected to shearing. The use of these advanced techniques can improve understanding, improve prediction accuracy, and develop robust engineering solutions.

In the current study, laboratory tests on sand soil (fine

Table1 Physical properties of used sands

Soil	G_S	D_{10}	D_{50}	C_U	C_C	e_{min}	e_{max}
Sand of Djamaa(S1)	2.65	0.20	0.38	2	1.20	0.50	0.75
Sand of El-Hadjeb (S2)	2.67	0.18	0.28	1.66	0.97	0.63	0.88

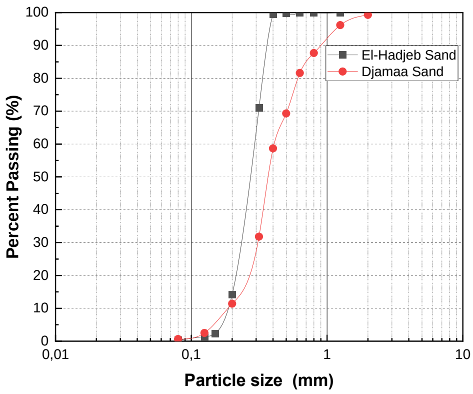
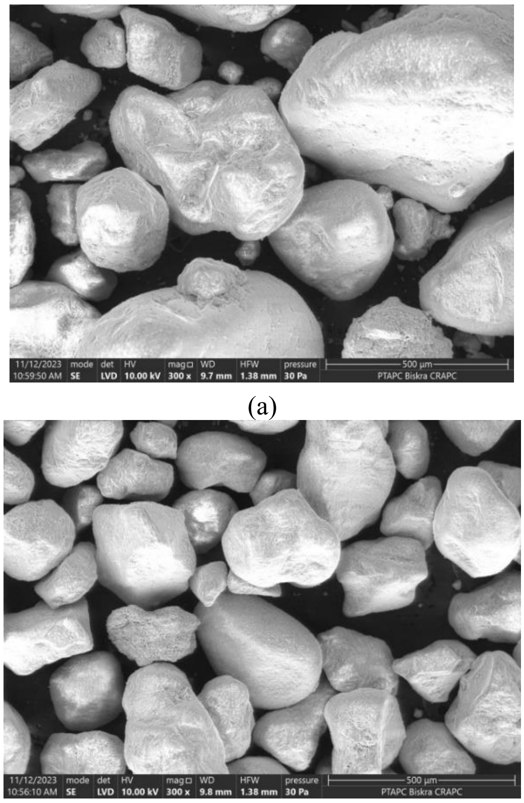


Fig. 1 Particle size distribution curves of dune sand



(a)

(b)

Fig. 2 SEM image of (a) Sand Djamaa (S1) and (b) Sand El-Hadjeb (S2)

and coarse) was investigated using the unconfined compression tests and high-resolution scanning electron microscopy. The results on the influence of different concentrations of xanthan gum, curing periods, and the combined effect of xanthan-polypropylene fibre content were presented and discussed.

2. Materials and methods

2.1 Materials

2.1.1 Dune sand

In this study, two types of dune sands (S1 and S2) were collected respectively from Djamaa in the city of Oued souf (S1), and El-Hadjeb, in the city of Biskra (S2) in the southern region of Algeria. These sands are classified as poorly graded sand (SP) according to the Unified Soil Classification System (USCS). The particle size distribution curves of the soils are shown in Fig. 1, and the soils physical properties are summarized in Table 1.

Fig. 2 presents the microscopic images of the two types of sands (S1 and S2, respectively) conducted in an SEM test. The Fig. shows the quantity of tested particles in the form is angular, where it differs in soil particle size.

Fig. 3 Xanthan gum used in this study

2.1.2 Xanthan gum Biopolymer:

The biopolymer in the present study was industrial-grade xanthan gum (XG), which is yellow powder at room temperature and can form gels with high consistency and viscosity in aqueous solutions. Xanthan gum ($C_{35}H_{49}O_{29}$) is an anionic polysaccharide, a biopolymer produced by Xanthomonas (Becker *et al.* 1998), Xanthan gum has been frequently utilized in the food industry due to its temperature stable, compatibility with food additives, and pseudoplastic rheological qualities (García-Ochoa *et al.* 2000). Moreover, xanthan gum is also employed as a gelling and suspending agent (flocculent) for viscosity control in the oil sector as a drilling mud thickener (Becker *et al*. 1998). Recently, many studies have applied xanthan gum in geotechnical engineering techniques due to its high soil strengthening efficiency and adequate economics (Lee

Table 2 Basic parameters of Polypropylene fibre

Type	Monofilament micro fibre(6mm)	Monofilament micro fibre(12 mm)
Cross section	Round	Round
Fibre length	6 mm +/- 1 mm	12 mm +/- 1 mm
Thickness	30-32 micron	30-32 micron
Tensile Strength	427-495 MPa	467-548 MPa
Modulus Elasticity	4457-5110 MPa	4048-5674 MPa
Elongation	20-25%	20-25%
Specific Density	0.91 g/cm^3	0.91 g/cm^3
Tenacity	High Tenacity	High Tenacity
Biological resistance	Stable	Stable
Color	Transparent	Transparent

et al. 2017, Cho 2019, Kwon *et al.* 2019, Lee *et al*. 2019, Lee *et al.* 2022), the commercial xanthan gum powder used in this study is shown in Fig. 3.

2.1.3 Polypropylene fibre

The fibre that was used in this study was polypropylene fibre, which is a synthetic material from PP polymer. Polypropylene fibre is an inert material with low heat conductivity and high resistance to acids, alkalis, and salts. It is commonly utilized to enhance sample toughness and increase the ductility of fibre-reinforced soils. The length of the monofilament fibre was 6 and 12 mm. The basic physical and mechanical parameters of polypropylene fibre are given in Table 2.

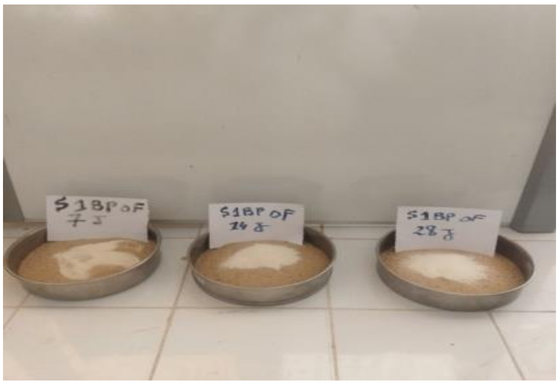
2.2 Sample preparation and test methods

2.2.1 Unconfined compressive strength test

Various xanthan gum and drying times are tested in this experiment. According to the absence of xanthan gum, clean fibre-reinforced sandy soil samples tend to become loose and weaken after drying, which does not accord with the requirements of the experimental method to evaluate the strength of the XG-treated sand specimens with or without fibre on different contents and curing age. The dry UCS represents the measured strength under hydrated conditions.

The dry UCS was evaluated after curing times for 7, 14 , and 28 days. The UCS tests for XG–fibre-treated soil was conducted in accordance with ASTM D1633-17, Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders, with uniform loading rate of 0.5 mm/min, unconfined compressive strength tests were performed by using a dispositive of the triaxial cell. To prepare soil samples for soil improvement; two methods are currently used: the dry mixing method and the wet mixing method as shown in Fig. 5. The dry method is more effective than the wet method in strengthening the material (Velde and Kiekens 2001). Therefore, the dry mixing method was used in this study. In this method, xanthan gum powder was mixed with dry sandy soil and fibre. The mixture was then stirred and molded into samples after adjusting it to a specific moisture content.

Fig. 4 Polypropylene fibre reinforcement used in this study



(a) Dry mixture

(b) Wet sample

Fig. 5 Sample preparation procedure

2.2.2 Experimental program:

The UCS tests as shown in Fig. 6 and SEM imaging were used to investigate the influence of biopolymer and fibre mixture on dune sand engineering properties, the UCS tests were performed to evaluate the mechanical properties of the Xanthan gum-treated sand, and SEM images were conducted to identify the microstructure of the treated sand. The experimental program of this study is shown in detail in Table 3.

Table 3 Experimental program in this investigation

Test Type	Soil Type	Biopolymer content (%)	Fibre content (%)		Dehydration Time (Days)
			6 mm	12 mm	
UCS	S1	[0.5, 1, 2]	-	-	7, 14, 28
	S2	[0.5, 1, 2]	-	-	7, 14, 28
	S1	0.5	0.5	-	7, 14, 28
	S1	0.5	0.75	-	7, 14, 28
	S1	0.5	1	-	7, 14, 28
	S2	0.5	0.5	-	7, 14, 28
	S2	0.5	0.75	-	7, 14, 28
	S2	0.5	1	-	7, 14, 28
	S2	1	0.5	-	7, 14, 28
	S2	1	0.75	-	7, 14, 28
	S2	1	1	-	7, 14, 28
	S2	2	0.5	-	7, 14, 28
	S2	2	0.75	-	7, 14, 28
	S2	2	1	-	7, 14, 28
	S2	1	-	0.5	7, 14, 28
	S2	1	-	0.75	7, 14, 28
	S2	1	-	1	7, 14, 28
SEM	S1, S2	-	-	-	-
	S1	2	-	-	28
	S2	2	-	-	28
	S1, S2	0.5	0.5	-	28

A two-class label technique in various curves, which used S1 for coarse sand and S2 for fine sand, was used to differentiate between various specimens. The first class was used for the sand combination, which consisted of three parts: S stands for sand class (a number 1 and 2), and XG is Xanthan gum with a content of (0.5, 1 and 2%). F as fibre content a number of (0.5, 0.75, and 1%). All specimens were cured for various curing times: 7, 14, and 28 days in the open air at a temperature range between 22 and 25°C.

The fibre content (Fc) of a composite is defined as a percentage of the dry mass of the sand, based on the proposed equation by (Anagnostopoulos *et al.* 2013);

$$\text{Fc}\,(\%) = (Wf/Ws) \times 100\,(\%) \quad (1)$$

Where: w_f and w_s are fibre and dry sand masses respectively.

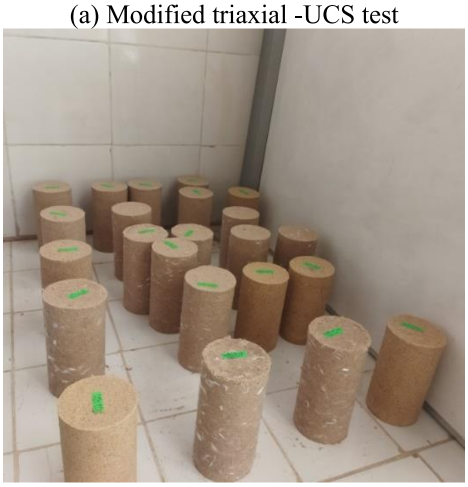
Xanthan gum was dry-mixed with soil at varying proportions (0.5%, 1%, and 2% of the dry weight of soil) and thoroughly hand-mixed (Bouazza *et al.* 2009, Chang *et al*. 2015).

2.2.3 Scanning Electron Microscope (SEM) images:

The change in the mechanical behavior of sand treated with a biopolymer and fibre mixture is further analyzed by a scanning electron microscope (SEM) study. The Thermo Scientific Prisma E Scanning Electron Microscope (SEM) was utilized to collect micro-scale pictures and EDS analysis of both xanthan gum with and without fibre-treated and untreated sands, as shown in Fig. 7.

Scanning Electron Microscopy (SEM) is a powerful imaging technique frequently used in the analysis of biopolymer-treated sandy soils. In this experiment, the essential properties of SEM imaging were utilized to reveal

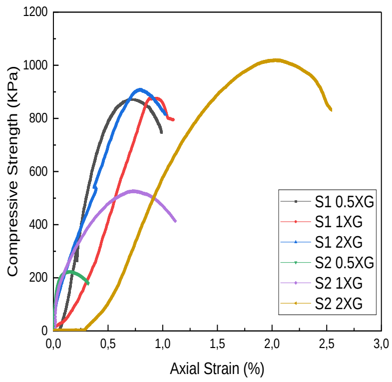
(a) Modified triaxial -UCS test



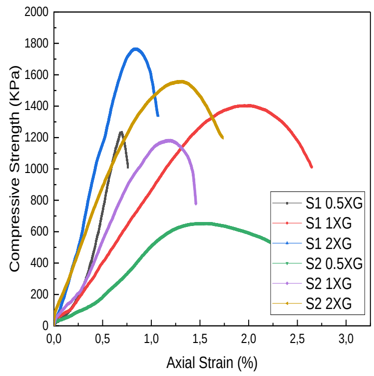
(b) Airing for curing samples

Fig. 6 Triaxial apparatus used in this study and the airing space for curing samples

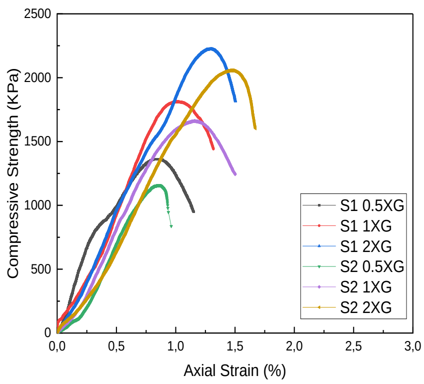
Fig. 7 Scanning Electron Microscope used in this study



(a) 7days



(b) 14 days



(c) 28 days

Fig. 8 Unconfined compressive strength of xanthan gum-treated sand

the variation in particle arrangement and the interaction between biopolymer and sand particles within the sample.
The test specimens, with dimensions of 10 mmx10 mmx4 mm, were obtained from a series of unconfined compressive strength (UCS) tests specimens and were placed in an oven at 45°C for 6 hours before the test. The Thermo Scientific Prisma E high- resolution field emission scanning electron microscope, as shown in Fig. 7, was employed in this study to observe the microstructure of the specimens. Different magnifications were used to better examine the effect of various contents of xanthan gum on the microstructure of fibre- reinforced sandy soil. on the other part the microscopic analysis parameters (voltage, acceleration, pressure .....etc) can be found in each reference figure.

3. Results

3.1 Unconfined compressive strength of Xanthan gum-treated dune sand

Unconfined compression tests were performed on Xanthan gum-treated S1 and S2 specimens considering

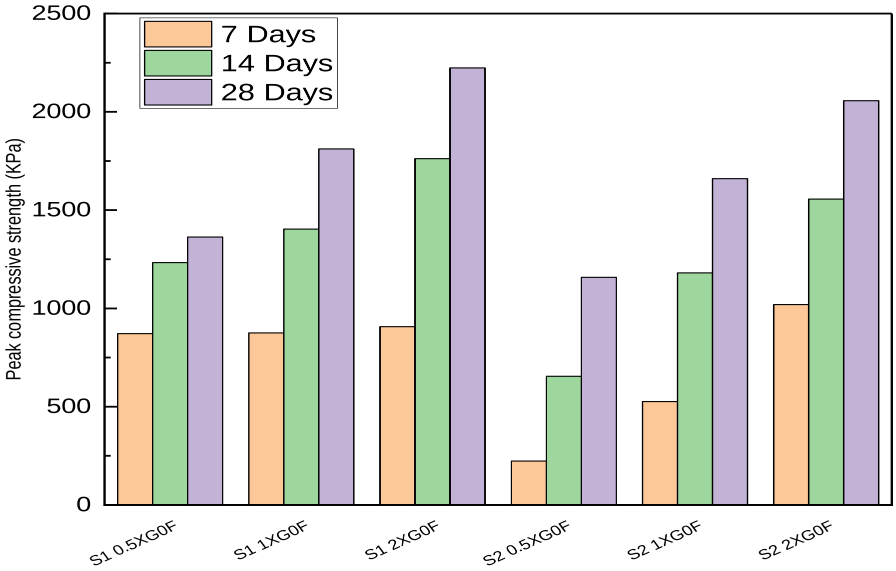


Fig. 9 Influence of XG content on the peak strength for different curing time

different curing age 7, 14 and 28 days. Typical plots of UCS strength-strain curves are presented in Fig. 8. The UCS of the untreated S1 and S2 is measured between average of 40 kPa and 32 KPa respectively. As shown in Fig. (8), when Xanthan is added at percentages varying between 0.5, 1, and 2%, the compressive strength increases with the increase of both xanthan content and the period of curing time. as can be seen for S1 samples mixed with 0.5% of XG, the compressive strength for 7, 14 and 28 days were respectively 871,793, 1232,792 and 1363,415 kPa. This results were reported by several studies indicating the effectiveness of using the biopolymer to provide the improvement of soil mechanical properties (Bagheri *et al.* 2023, Chang *et al.* 2016, Kwon *et al.* 2019, Chang and Al-sadarani 2017). From the Figs. 8(b) and 8(c), it was shown that Xanthan gum enhances compressive strength for various contents and increases the axial strain of failure to the strain hardening. The increase in strength could be due to the capacity of xanthan gum to bind sand particles, which leads to better cohesion. There was an increase in strength as a result of the formation of a cohesive matrix, which effectively resisted compressive loads. An increase in the compressive strength in the 28 days of curing time was also observed. The stress peak increases with the content of xanthan gum, indicating an increase in compressive strength; similar results were mentioned by (Chang *et al.* 2020, Lee *et al.* 2019b, Wang *et al.* 2021).

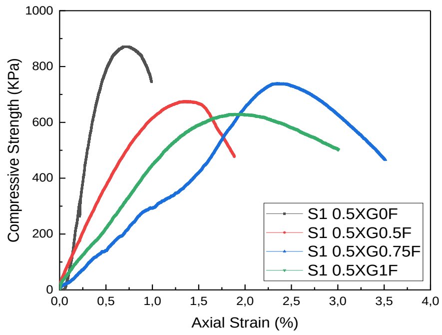
3.2 Effect of Xanthan gum-treated dune sand on UCS_{max}

The results maximal compressive strength of treated sand with Xanthan gum biopolymer is presented in Fig. 9.

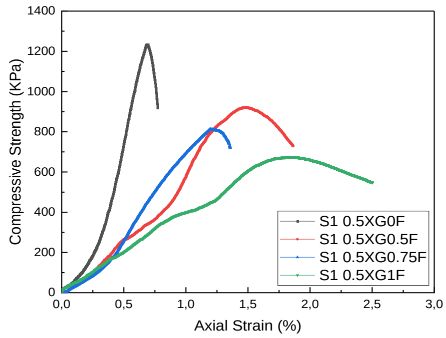
The Results have shown for 28 days of curing time that adding 2% of XG to S1 soil samples leads to an increase in the UCS_{max} about 55,58% in maximum UCS, and of about 64% for soil S2 mixed with 2% of XG. It is to note that, the effect of xanthan gum and curing age are significant on the two types of sands; for the same concentration of Xanthan gum, the coarse sand S1 was more resistant than the fine sand S2, this finding can be explained by the important volume of voids which contains the coarse sand S1. Hence, the xanthan gum biopolymer fills the void between sand grains; unlike the fine sand, there is a small strength because the morphology is different from the coarse sand, so in this case, the xanthan gum fills the same pore. For this, it is less than strength. As shown in the SEM test, this result was confirms the finding reported by (Chang *et al.* 2015, Lee *et al.* 2019a, Ma 2023).

4. Effect of fibre content on unconfined compressive strength of xanthan gum treated sand:

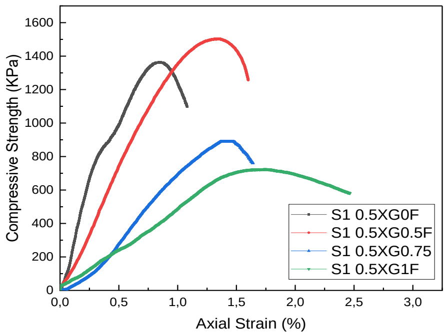
Fig 10 illustrates the compressive strength of unreinforced treated sand and reinforced treated sand specimens with 0.5% xanthan gum. The graph shows the results of UCS for different fibre contents of Fc= 0, 0.5, 0.75, and 1% and curing periods of 7, 14, and 28 days respectively. It can be seen for fibre reinforced S1 sand that the incorporation of fibre initially decreases the strength for 7 and 14 day of curing periods, then the soil increases it strength by reducing the brittleness for a 28-day of curing period. As shown in Fig 10 (d, e, and f), the results indicate also that the ductility of all specimens enhanced directly with the addition of reinforcement when age of curing ranges between 7 to 14 days. and it decreases in 28 days.



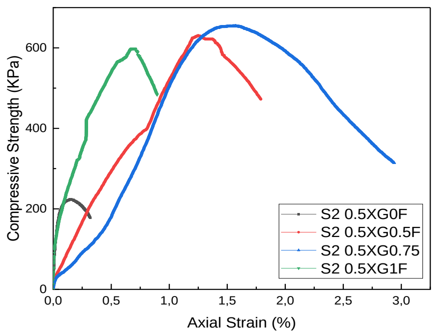
(a) S1 7 days



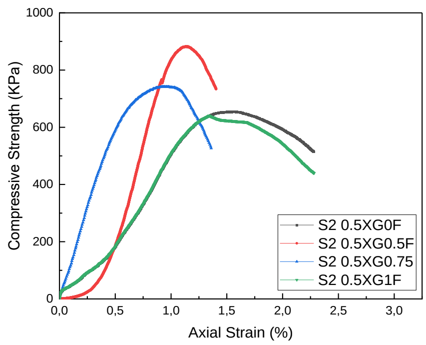
(b) S1 14 days



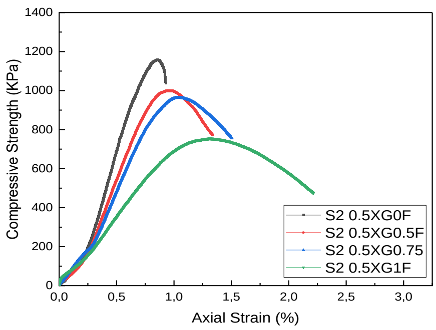
(c) S1 28 days



(d) S2 7 days



(e) S2 14 days



(f) S2 28days

Fig. 10 Effect of fibre content on Xanthan gum treated sand

4.1 Peak compressive strength for all samples:

4.1.1 Variation of Peak compressive strength of fins sand treated with différents XG content and fibre content:

Fig. 11 shows the evolution of peak compressive strength of fine sand (S2) treated with xanthan gum in various concentrations and reinforced with different percentages of fibre, with different curing periods times; 7, 14 and 28 days. The results show that the peak compressive strength increases with time and biopolymer concentration. This is similar with the obtained results of (Sujatha 2021). Biopolymers exhibits the maximum increases of strength and effectively harden in soil as it dries. Considering the combined effect of fibre on the treated sand, it was shown after 7 days of curing that the maximum compressive strength is obtained for sand treated with Xanthan gum (XG), where each percentage of fibre tends to decreases the peak of compressive strength of xanthan treated sand (S2).

Therefore was excluded from further research. This is because xanthan gum promising effect on strength improvement and the fibre effect the ductility of mixture, but when the fibre content is more 0.5%, the high fibre content don’t create a compatibility when mixed with xanthan gum, the peak strength decrease when fibre content increase. However, it is possible that a higher concentration of fibre content would have a larger impact on compressive strength as mentioned by (Chen *et al.* 2022).

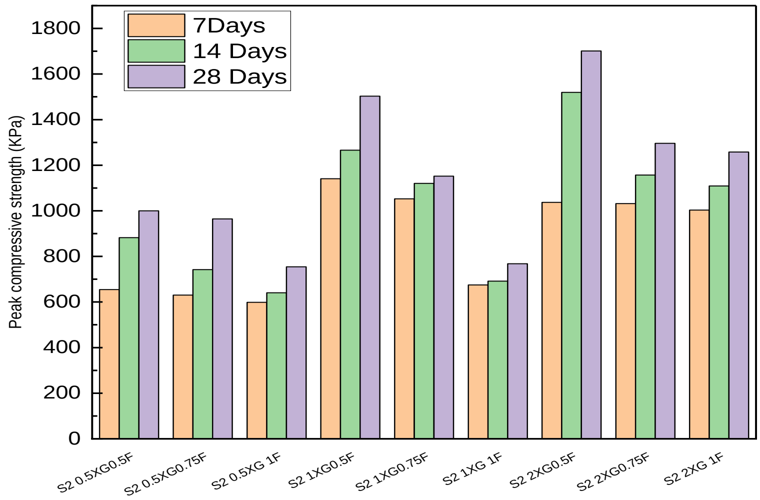


Fig. 11 Influence of fibre and XG content on Peak strength with different curing period

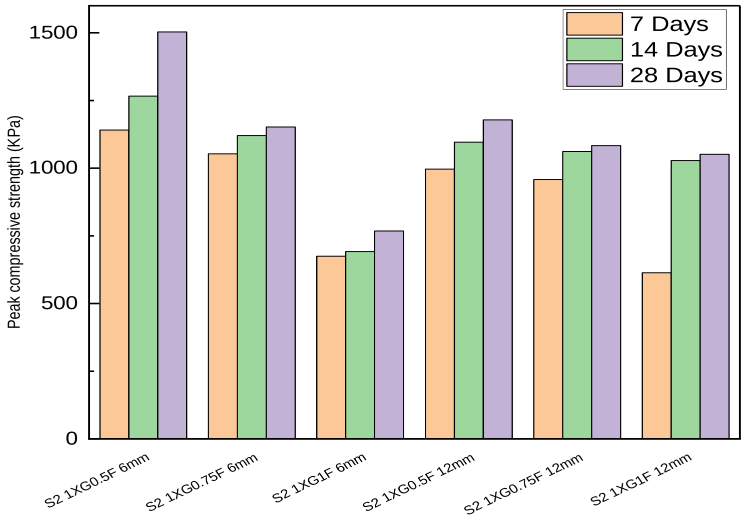


Fig. 12 Effect of fibre length on Peak compressive strength

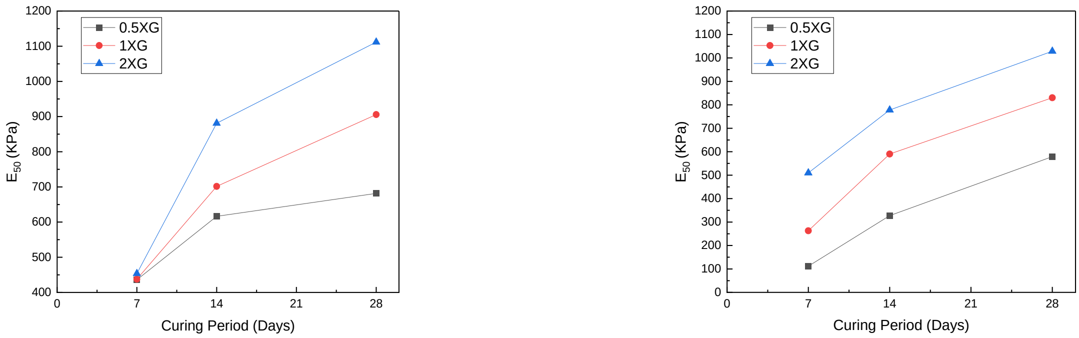
4.1.2 Effect of fibre length and XG content on peak strength of fine sand:

The peak strength of fine sand treated with constant XG content and reinforced with two different fibre lengths, the fibre length is 6 mm and 12 mm is shown in Fig. 12. The peak strength of the treated sand (S2) with 1% of XG and reinforced with fibre increased initially to 1500,1 KPa and then decreased with an increase in polypropylene fibre length at different curing time. The peak strength reached its highest level at a fibre length of 6 mm for 1% Xanthan gum and 0.5 % of fibre with curing time of 28 days, which represent the maximum strength. In the other hand, the peak strength with fibre length of 12 mm less than the peak strength with the 6 mm of fibre length, this is because the fibre content was higher and there were more pores as shown in microstructure image Fig. 15 in this condition the peak strength decrease with the increase of fibre content and fibre length, This result is similar to the results reported by (Li *et al*. 2017).

5. Effect of xanthan gum and fibre content on E50 with different curing times

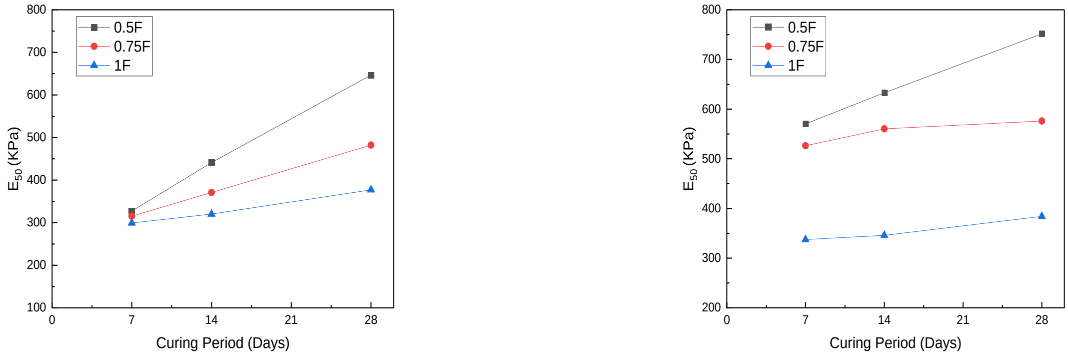
5.1 Effect of XG content on E50 with different curing times of coarse sand

Figs. 13(a) and 13(b) illustrate the behaviour of sand

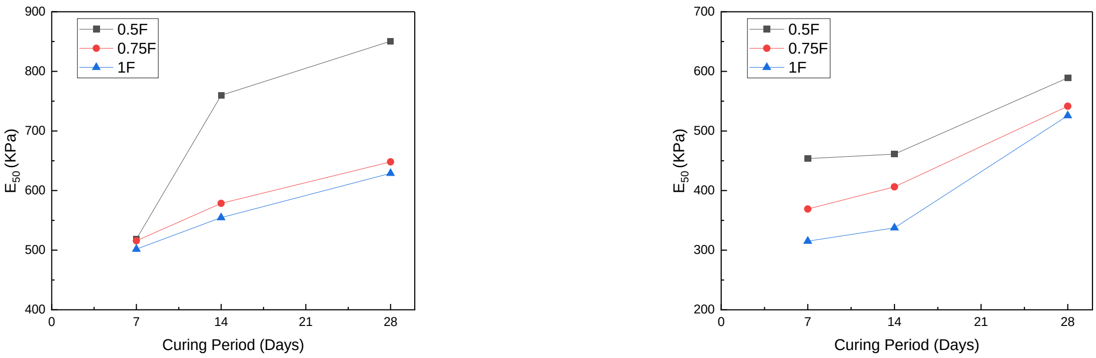


(a) S1 (b) S2

Fig. 13 Effect of Xanthan gum content on E50 modulus with different curing time



(a) S2 0.5XGF (b) S2 1XGF



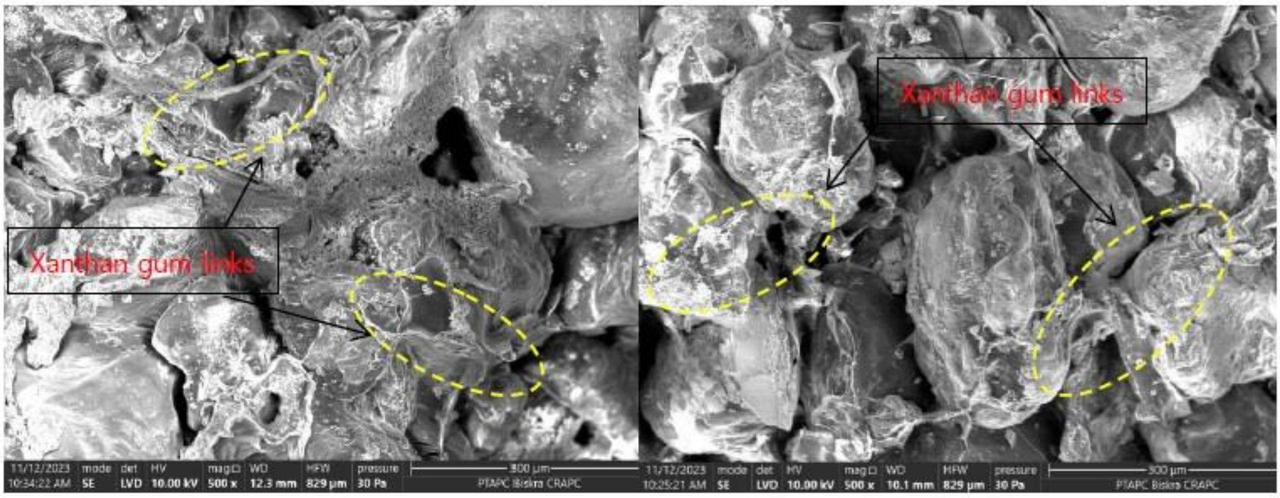
(c) S2 2XGF (d) S1 0.5XGF

Fig. 14 Effect of fibre content and XG on E50 modulus with different curing time

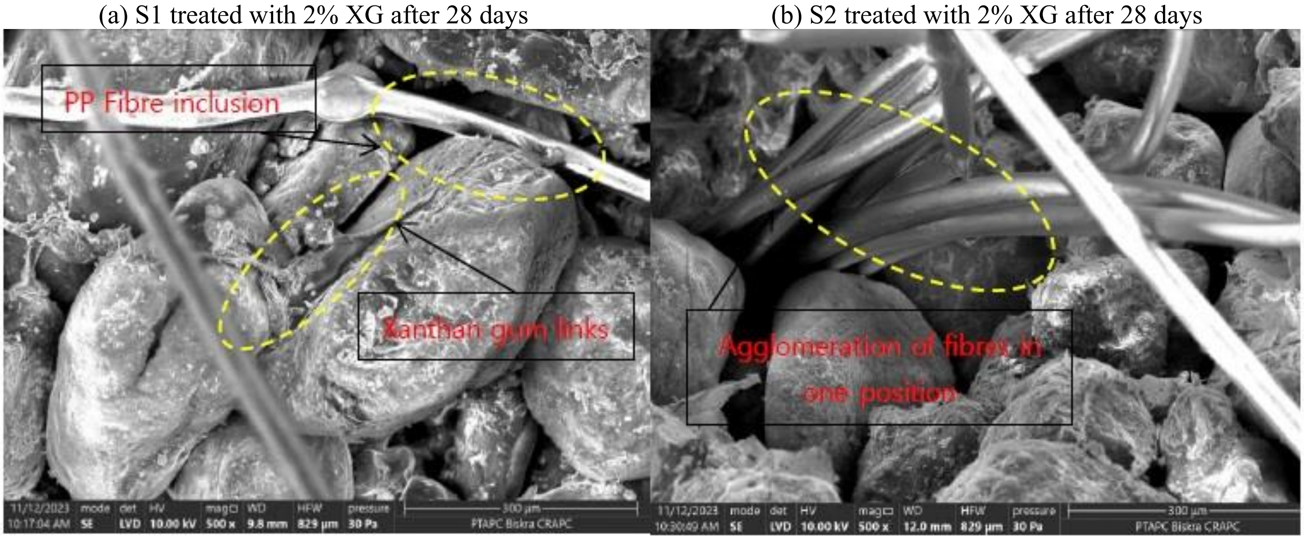
treated with 0.5%, 1% and 2% added xanthan gum for different curing periods. The results showed a significant effect of treatment with XG on secant modulus, with secant modulus increasing with increasing XG content, weakening the stabilised soil due to hydration of the hydrogels. However, over time, dehydration of the hydrogels associated with agglomeration of the soil particles occurs, contributing to the increase in qu and E50. This observation is in line with the results of previous studies (Chang *et al.* 2015, Chang and Al-Sadarani 2017).

5.2 Effect of Fibre content and Xanthan gum mixture on E50 with different curing times:

Figs. 14(a)-14(c) show the results of biostabilization with XG. The addition of 0.5% fibre content and 2% XG induced an increase in E50 with increasing curing time, with a maximum of E50 of 850.655 KPa. However, the secant Young modulus of treated sand with added fibre decreased as the fibre content increased. If the fibre content is too high, agglomeration can occur, resulting in irregular XG content and reduced strength.



(a) S1 treated with 2% XG after 28 days (b) S2 treated with 2% XG after 28 days



(c) S1 with 2XG0.5F after 28 days (d) S2 with 0.5XG0.5F after 28 days

Fig. 15 Micro structure of sand treated by Xanthan gum and reinforced with fibre

When comparing Figs. 14(a)-14(d) for a sand mixture treated with 0.5% XG and reinforced with different percentages of fibre, it is observed that the reinforcement with polypropylene fibres is more effective when the soil has a minimum void volume. However, the fibres tend to increase the volume of the mixture. Therefore, this results can be confirmed for fine sand samples reinforced with 1% of PP fibre where the UCS strength keep to a close value for all periods of curing time.

6. Microscopic structure of Xanthan Gum-fibre mixture treated dune sand

Figs. 15(a)-15(d) illustrates the photomicrographs of treated dune sand XG and reinforced with PP fibre. SEM images indicate that the incorporation of fibres and xanthan gum can enhance the microstructure of sand. The creation of a three-dimensional network between sand particles, fibres, and xanthan gum molecules can bind the sand particles together and reduce the voids between the particles, same results obtained by (Dehghan *et al*. 2019). This decrease in voids contributes to a more compact and coherent microstructure which results in a better mechanical performance of the sand. The enhanced microstructure of the sand can be explained by the following factors: Fibres play the role of reinforcement, which helps to prevent the sand particles from moving relative to each other. Secondly, xanthan gum functions as a binding agent (Chang *et al*. 2015), contributing to the cohesion of the sand particles. Finally, the formation of a three-dimensional network among the sand particles, fibres, and xanthan gum molecules contributes to the more even distribution of load throughout the sand mass, The high content of fibre produced a conglomerate. The fibre content and distribution affected the XG distribution and the location of XG formation. Under the same test conditions, a high fibre content or longer fibre length results in less XG formation on the fibre surface. This last factor effects the reduction in compressive strength.

7. Conclusions

A series of laboratory experiments, including unconfined compressive strength tests and SEM tests, were conducted as part of this research to quantify the strength improvements of soils reinforced with xanthan gum biopolymer and polypropylene fibres. Due to the wide range of problematic soils and the importance of environmental issues, sandy soils were selected for this research. Here are the main conclusions:

- Adding xanthan gum (XG) to a sandy soil increases its ductility, i.e., its ability to deform under the effect of increased stress. In this context, this improvement is directly proportional to the concentration of XG.
- The reinforcing of soil using xanthan gum (XG) leads to a moderate increase in strength and stiffness. This enhancement is only visible when the curing duration exceeds 7 days and the XG content is greater than 0.5 %.
- During the first seven days of the treatment process, bio stabilization has a limited impact due to its tendency to degrade quality. This degradation is linked to the potential wetting of the hydrogels.
- The reinforcement by PP fibres has a negative effect in coarse sand in general and fine sand in particular with the same XG dosage (0.5%), i.e., the presence of fibres with a high content creates more voids which increase the volume of the matrix, which affects the reduction in resistance.
- The results indicate that the addition of XG improves the strength of fibre reinforced sand samples.
- SEM images show the effectiveness of xanthan gum as a binder for treating dune sand, xanthan gum fills the voids between sand particles, creating bridges that increase resistance in coarse sand.

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