Geomechanics and Engineering, *Vol. 26, No. 2 (2021) 101-115*
https://doi.org/10.12989/gae.2021.26.2.101

Experimental investigation on the shear strength and deformation behaviour of xanthan gum and guar gum treated clayey sand

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(Received August 1, 2020, Revised May 15, 2021, Accepted June 25, 2021)

Abstract. Soil stabilization is widely used to favourably amend the soil behaviour. The use of biopolymers to treat soil is not only an eco-friendly but is also a sustainable approach. Biopolymers, xanthan gum and guar gum are used to augment the strength of clayey sand. Xanthan gum is anionic while guar gum is non-ionic. Triaxial tests were conducted on treated soil samples to understand the effect of biopolymer treatment on clayey sand at different dosages and curing periods. Shear strength parameters –angle of internal friction and cohesion increases appreciably on treating soil with xanthan and guar gum for all dosages investigated, though angle of internal friction decreases with the curing period in case of xanthan gum treated soil. Xanthan gum performs better in enhancing the strength and deformation behaviour of the soil compared to guar gum. There is a substantial gain in early strength but as the curing period increases further, the rate of increase in strength is marginal. The deformation modulus at failure also increases with the biopolymer content. The reduction in post-peak strength of treated soil is sudden and drastic indicating brittle behavior. The energy absorption capacity of the biopolymer treated soil increases with increase in biopolymer content and curing period. The strength gain in soil can be ascribed to the formation of hydrogels that are cementitious in nature. Strength is also improved through the ionic / hydrogen bonds that are formed by biopolymer addition.

Keywords: cohesion; deformation modulus; energy absorption capacity; friction angle; guar gum; Xanthan gum

1. Introduction

1.1 Background

Stabilizing problematic soil for various geotechnical applications is a common and almost mandatory construction activity off-late, though the practice of soil improvement dates back to the early ages of civilization. Weak soils characterized by inadequate strength and high susceptibility to volume change require soil improvement. Conventional soil improvement techniques include the addition of cementitious material like lime, cement, fly ash and other bituminous material (Wang *et al.* 2020, Alrubaye *et al.* 2018, Oluwatuyi *et al.* 2020). But these conventional additives like cement, lime, etc., affect the nature of the soil, groundwater, vegetation growth and involve the generation of greenhouse gases like nitrous oxide and carbon dioxide in the production stage (Chang *et al.* 2016a, 2019a, Arab *et al.* 2019).

These limitations impose the need for non-conventional additives to amend the geotechnical properties of the soil. Adapting to eco-friendly additives is the need of the hour to combat pollution and aid sustainable development. Biopolymers, the natural polymers derived from biological sources, are now widely tested for their capacity to modify the nature of problematic soils favorably (Chang and Cho 2012, 2014, Chang *et al.* 2016b, Muguda *et al.* 2017, Sujatha and Saisree 2019, Kumar and Sujatha 2020, Ghasemzadeh *et al.* 2020a, Soldo *et al.* 2020). Also, biopolymers find applications in the other engineering fields and are extensively used in the food industry, medicinal field, oil recovery, etc. (Chang and Cho 2014).

The numerous advantages of using biopolymers are: they are eco-friendly, renewable and do not contribute to greenhouse gas emissions (Chang *et al.* 2016a, Lee *et al.* 2019). A thorough study on the choice of biopolymers to modify the soil properties demonstrates that xanthan gum and β-glucan were used for preventing soil erosion and desertification (Maghchiche *et al.* 2010, Chang *et al.* 2015c, Qureshi *et al.* 2017). Some authors studied the possibility of creating temporary hydraulic barriers in sand and silt using xanthan gum, guar gum, gellan gum, β-glucan and sodium alginate (Bouazza *et al.* 2009, Chang *et al.* 2019c, Kumar and Sujatha 2020). Their studies report that treating the soil with the above said biopolymers noticeably reduced their hydraulic conductivity.

1.2 Previous studies

Table 1 presents the summary of the literature reporting the use of biopolymers for several geotechnical applications.

1.3 Need for research

The choice of biopolymers for field applications has not

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http://www.techno-press.org/?journal=gae&subpage=7 ISSN: 2005-307X (Print), 2092-6219 (Online)

Table 1 Recent studies in soil stabilization using biopolymers

S.No.	Soil type	Biopolymer used	Optimum content	Results	Reference
1	Korean residual soil	β -1.3/1,6- glucan	-	Improves the strength	(Chang and Cho 2012)
2	Fontainebleau sand	Agar, Starch	-	Enhancement in cohesion and Stiffness	(Khatami and Kelly 2013)
3	Korean residual soil	β -1.3/1,6- glucan	-	Enhances shear modulus and decrease permeability	(Chang and Cho 2014)
4	Sand, Sand with silt, Clay, Residual soil	Xanthan gum	1-1.5%	Strengthening is dependent on soil type, biopolymer content, hydration and mixing method	(Chang *et al.* 2015a)
5	Organic Peat	Xanthan gum	2%	The gain in shear strength	(Latifi *et al.* 2016)
6	Collapsible soil	Xanthan gum, Guar gum	2% Guar gum	The decrease in collapsible potential and an increase in shear strength	(Ayeldeen *et al.* 2017)
7	Desert Sand	Xanthan gum	2-3%	Improvement in various mechanical properties	(Qureshi *et al.* 2017)
8	Sand	Xanthan gum	2%	Higher-strength in the resubmerged state	(Lee *et al.* 2017)
9	Sharp sand with kaolin and gravel	Xanthan and guar gum	-	Improvement in mechanical properties of soil	(Muguda *et al.* 2017)
10	Silty clay	Xanthan gum, Guar gum	2% Xanthan gum	Decrease in permeability and collapsible potential	(Dehghan *et al.* 2019)
11	Silty soil	Casein	5%	Shows high strength and enhance erosion resistance	(Chang *et al.* 2018)
12	Sand	Polyurethane resin	-	Increase in unconfined compression strength and tensile strength	(Liu *et al.* 2018)
13	Sand clay mixtures	Gellan gum	1%	Increase in the shear strength parameters	(Chang and Cho 2018)
14	Marine clay	Xanthan gum, ϵ-polylysine	2%	Enhancement in strength	(Kwon *et al.* 2019)
15	Sand	Xanthan gum	2%	Strength enhancement	(Lee *et al.* 2019)
16	Clay	Vinyl acetate	-	Increase in strength and promoting vegetation growth	(Song *et al.* 2019)
17	Sand	Xanthan gum	-	Drying leads to increase strength and cohesion	(Chen *et al.* 2019)
18	Clay	Guar gum	2%	Strength gain and reduction in compressibility	(Sujatha and Saisree 2019)
19	Silty sand, pure sand and high plasticity clay	Xanthan gum	1%	Enhancement in shear strength	(Soldo and Miletić 2019)
20	Sand with Silt	Xanthan gum, β 1,3/1,6 glucan, Chitosan, Guar gum, and Alginate	2% Xanthan gum and 1% Guar gum	Soil strength improvement	(Soldo *et al.* 2020)
21	Clayey sand	β -glucan	-	Strength enhancement	(Kumar and Sujatha, 2020)

gained adequate impetus yet as there are only limited experimental findings that support their use in the field and warrant more qualitative research in this direction. A thorough survey of literature on biopolymer treated soil (BTS) shows that there are no detailed investigations on the effect of biopolymer treatment on clayey sand and identification of the mechanism of their strength gain with biopolymer addition, particularly on soils in Southern India. Their free draining nature and early collapse behavior are some of the major construction difficulties. Previous studies were limited to soil types like sand, silt and clay (Khatami and Kelly 2013, Qureshi *et al.* 2014, Latifi *et al.* 2017, Chang *et al.* 2019b, Sujatha and Saisree 2019).

Authors like Dehghan *et al.* (2019) and Soldo *et al.* (2020) have compared the shear strength enhancement in xanthan gum and guar gum treated soil by using an unconsolidated undrained (UU) triaxial test. But an exhaustive investigation on the impact of biopolymer dosage, confining pressure, and curing period is necessary understand the strength gain mechanism further.

1.4 Scope of the study

This study emphases the deformation and strength behavior of clayey sand treated with two different biopolymers viz. xanthan and guar gum using triaxial shear tests under different confining pressures in the UU condition. Despite the fact that consolidated triaxial tests are generally used to determine the strength of the soil, numerous researchers propose to utilize the UU-triaxial test on the grounds that adding water to BTS would alter or impede the strength of the soil (Qureshi *et al.* 2014, Dehghan *et al.* 2019, Soldo and Miletić 2019, Soldo *et al.* 2020, Kumar and Sujatha 2020).

The influence of the air-curing (drying) period on the BTS samples was investigated for a period of 28 days. The strength gain is expressed in terms of the improvement in the bearing capacity of BTS over untreated soil. The study also attempts to understand the strength gain mechanism by investigating the changes in microstructures, surface morphology and molecular groups of the untreated soil (UTS), xanthan gum treated soil (XGTS), and guar gum treated soil (GGTS) using the micrographs from a scanning electron microscope (SEM) and Fourier Transform Infrared Spectroscopy (FTIR) analysis. The economic and environmental advantage of using biopolymers like xanthan gum and guar gum over conventional cement-treated soil is also investigated.

2. Geomaterial and biopolymers

2.1 Soil

The soil for the study was taken from Tiruchirappalli (a city in Southern India) from trenches 1.5 m deep. The soil grains are in general sub-angular in shape (Fig. 1).

The liquid limit of the soil and its plasticity index is 22.5% and 7.33% resepectively. The soil is classified as clayey sand 'SC' as per the Unified Soil Classification System. The soil has low to medium dry strength and allows free drainage. Table 2 describes the various properties of the soil.

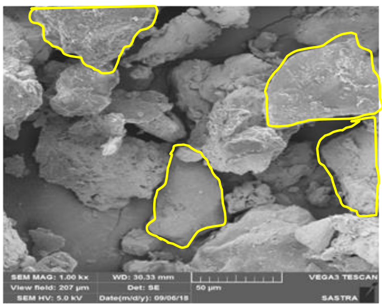


Fig. 1 Micrograph of UTS obtained from SEM

Table 2 Soil properties

Properties	Value
D_{10} (mm)	0.95
D_{50} (mm)	1.9
Coefficient of uniformity (C_u)	2.68
Coefficient of Curvature (C_c)	0.8
Specific Gravity (G)	2.3
Dry Unit weight γ_d (kN/m^3)	18.98
Optimum moisture content (%)	10
Cohesion (kPa)	62
Friction Angle (°)	28°

2.2 Xanthan and guar gum

Xanthan gum (XG) is an anionic biopolymer derived from the fermentation of sugars by the bacteria *Xanthomonas campestris* (Rashid *et al.* 2017, Kumar and Sujatha 2021). Its molecular weight is approximately 2 million g/mol (Katzbauer 1998). It is stable in both acidic and alkaline environments generally and is deemed as a thermo-stable biopolymer (Katzbauer 1998, Chang *et al.* 2015b, Ayeldeen *et al.* 2016).

Guar gum (GG), a plant-based natural biopolymer, is derived from the *Cyamopsis tetragonoloba* and is non-ionic in contact with water (Ayeldeen *et al.* 2017, Soldo *et al.* 2020, Kumar *et al.* 2021). Its molecular weight is 0.9 million g/mol (Venugopal and Abhilash 2010). It forms a high-viscous solution when hydrated and is minimally affected by pH and temperature (Bouazza *et al.* 2009, Sujatha *et al.* 2020).

The high viscosity and bio-clogging nature of both the biopolymers through the formation of gel-plug in the soil matrix help in modifying the nature of the soil (Ghasemzadeh *et al.* 2020a). XG and GG were purchased in powder form from a local market in Chennai, India. Dynamic viscosity of both the biopolymers at 50 rpm was determined using the Brookfield digital viscometer and their viscosity is presented in Table 3.

Table 3 Dynamic viscosity of the investigated biopolymers

Biopolymer & Content	Viscosity (cP)			
	0.5%	1%	1.5%	2%
XG	615	1566	3095	3887
GG	144	2064	3011	3625

a) Biopolymer treated soil
b) Compacted soil in split mould
c) Prepared samples

Fig. 2 Preparation of BTS samples

3. Experimental investigation

3.1 Sample preparation

Literature shows that the optimum biopolymer content varies from 0.5% to 2% for various types of soil (Krol *et al.* 2016, Lee *et al.* 2019, Sujatha and Saisree 2019, Kumar and Sujatha 2020, Soldo *et al.* 2020). Hence, 0.5%, 1%, 1.5% and 2% biopolymer content were used for this study. The dry mixing method was adopted for the preparation of the triaxial samples as suggested by the authors Chang *et al.* (2015b) and Latifi *et al.* (2017). Biopolymer was added to soil in the required percentage as dry powder and mixed with distilled water for molding the samples. Samples were hand-mixed using a palette knife to obtain a homogeneous mixture (Fig. 2(a)). The thoroughly mixed soil samples were molded at their respective optimum moisture content (Figs. 2(b) and 2(c)) and dry unit weights. Samples were air-cured (dried) for 1, 7 and 28 days at an average room temperature of 27°±2°C (Ghasemzadeh *et al.* 2020b, Dehghan *et al.* 2019, Lee *et al.* 2019).

3.2 Testing programme

Table 4 Summary of the testing programme

S.No.	Variable	UU triaxial test	SEM images	FTIR
1	Untreated Soil	UTS	UTS	UTS
2	XG Content (%)	0.5, 1, 1.5 & 2	0.5 & 2	2
3	GG Content (%)	0.5, 1, 1.5 & 2	0.5 & 2	2
4	Dry Density	MDU	-	-
5	Water Content	OMC	-	-
6	Curing Time (days)	1, 7 & 28	1 & 28	28
7	Confining Pressure (kPa)	50, 100 & 200	-	-
8	Standard	ASTM D2850-87	-	-

Triaxial test under unconfined undrained (UU) condition (ASTM D2850-87) was conducted to infer the strength of the soil before and after treatment with biopolymers at confining pressures of 50, 100 and 200 kN/m^2 on treated samples air-cured (i.e., at 27°±2°C) for 1 day, 7 days and 28 days after treatment (Fig. 2©). Table 4 details the summary of the experimental testing program. Three sets of samples were tested for different biopolymer contents and curing periods. Micrographs from SEM were used to understand the formation of hydrogels and gel-plugs in the BTS. FTIR analysis was carried out for UTS and 2% XGTS and 2% GGTS to understand the change in molecular groups and their effect on strengthening after treatment.

4. Results

The study shows that the type of biopolymer, dosage of biopolymer, confining pressure and the curing time affect the strength of BTS. The impact of these parameters on stress-strain behavior, failure strain, deformation modulus, cohesion, angle of internal friction, failure pattern (Fig. 3) and ultimate bearing capacity are discussed below.

4.1 Deformation behavior

4.1.1 Stress-strain response

The stress-strain response of XGTS and GGTS for various dosages of biopolymer and confining pressures are shown in Figs. 4-6. In general, GGTS resists loads with a gradual increase in strain, shows a clear peak and has a gradual reduction in post-peak strength after a 1-day of curing at all confining pressures (Fig. 4(d)-4(f)). The soil fails with clear peak stress and shows a drastic reduction in post-peak strength at all confining pressures after 7-days and 28-days curing period as shown in Figs. 5 and 6. XGTS shows a clear peak with a significant reduction in post-peak strength at all confining pressures and curing periods investigated (Figs. 4-6) and the samples fail by complete crushing, particularly after 7 days and 28 days of curing (Fig. 3(a)). GGTS fail by bulging during the early curing period, but the increase in the curing time shows a similar failure pattern as that of XGTS (Fig. 3(b)).

Peak deviatoric stress increases with the confining pressure, biopolymer content and days of curing for both the XGTS and GGTS. The peak deviatoric stress increased

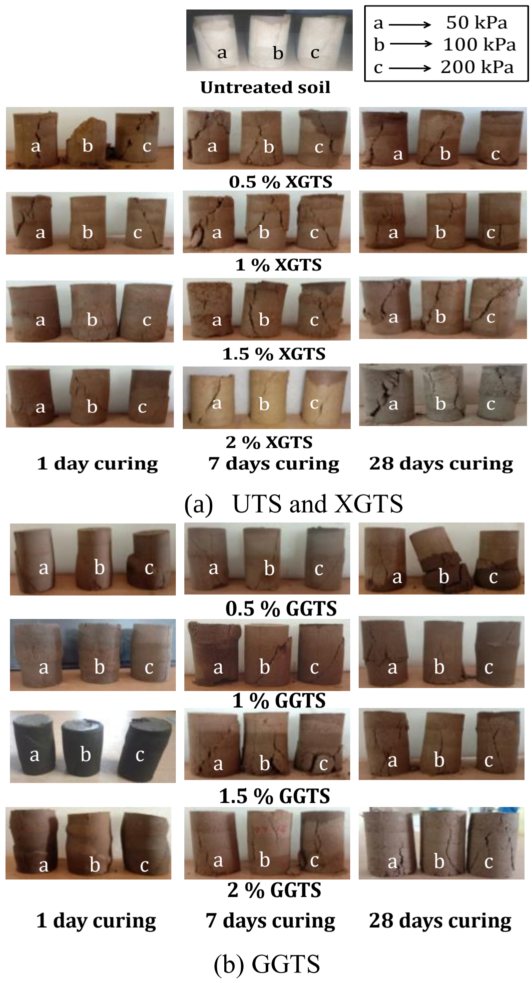


Fig. 3 Failure patterns of the UTS, XGTS and GGTS for all confining pressures and curing periods

11 times and 10 times that of UTS when treated with 2% of XG and GG respectively at 50 kPa confining pressure after 7 days of curing.

Figs. 4-6 demonstrate that at confining pressures of 100 kPa and 200 kPa, a marked increase in peak deviatoric stress is observed with the increase in biopolymer content and days of curing. For example, peak stress increases from 298 kPa to 406 kPa (1.4 times) in the case of UTS, 6100 kPa to 6659 kPa (1.1 times) for 2 % XGTS and 4074 kPa to 5832 kPa (1.4 times) for 2% GGTS when the confining pressure increased from 50 kPa to 200 kPa after 28 days of curing. XGTS shows higher peak deviatoric stress at all confining pressures and curing periods investigated than GGTS. The peak deviatoric stress of XGTS is 1.46, 1.45 & 1.42 times higher than that of GGTS at 0.5 % and 1.50, 1.18 & 1.14 times at 2 % biopolymer content for the confining pressures 50 kPa, 100 kPa and 200 kPa after 28 days curing, respectively. These results concur with the results presented in the literature of the BTS under UU-triaxial tests for various confining pressures showing that biopolymer can enhance the peak deviatoric stress (Soldo *et al.* 2020; Kumar and Sujatha 2020; Soldo and Miletić 2019; Dehghan *et al.* 2019). The failure strain of BTS, in general, tends to increase with the increase in confining pressure and curing period.

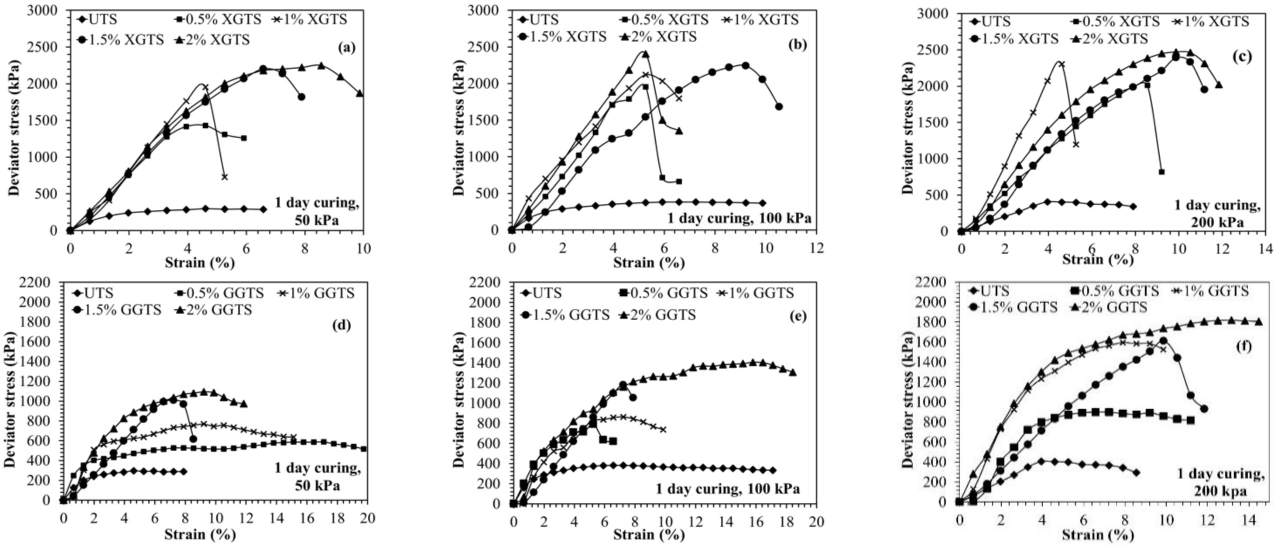


Fig. 4 Stress-strain behavior of UTS, XGTS and GGTS for various confining pressures – 1 day curing period

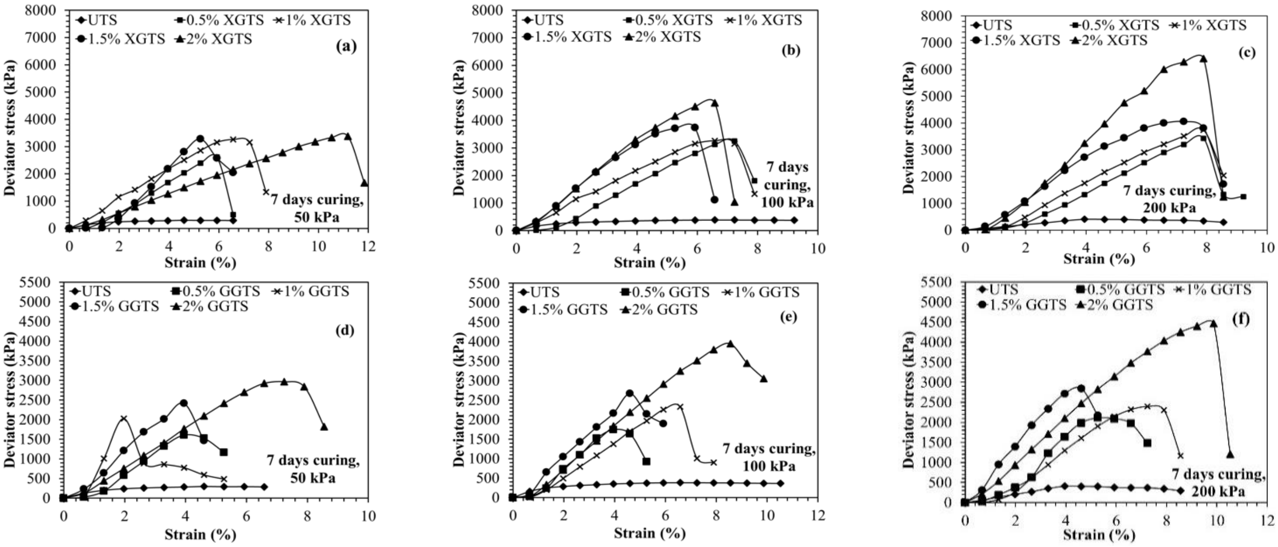


Fig. 5 Stress-strain behavior of UTS, XGTS and GGTS for various confining pressures – 7 days curing period

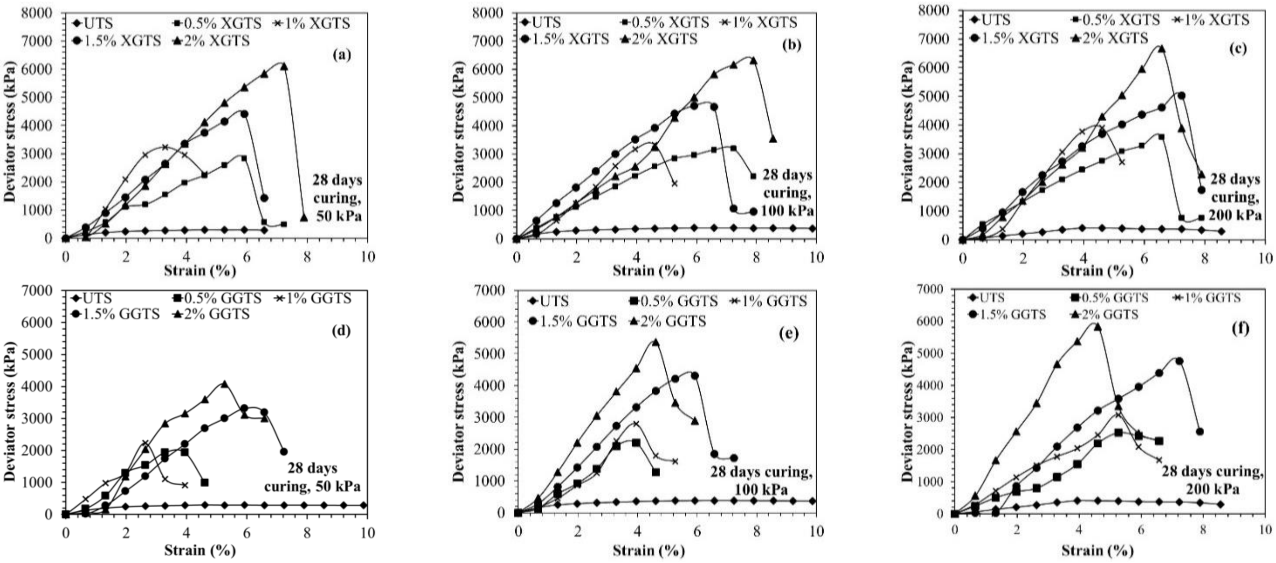
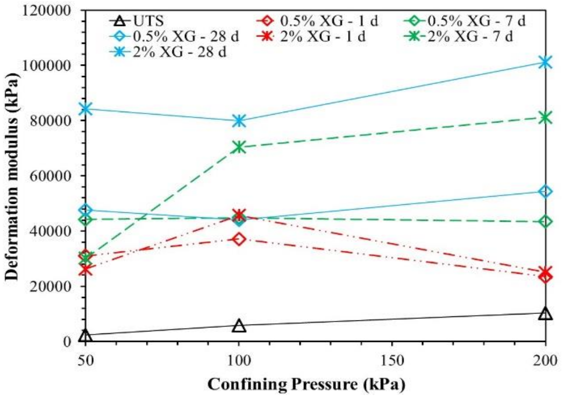
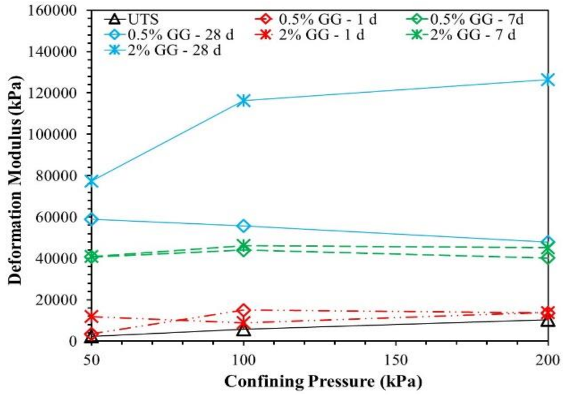


Fig. 6 Stress-strain behavior of UTS, XGTS and GGTS for various confining pressures – 28 days curing period

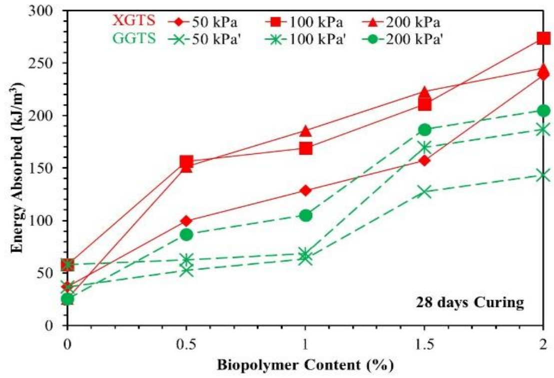


(a) XGTS

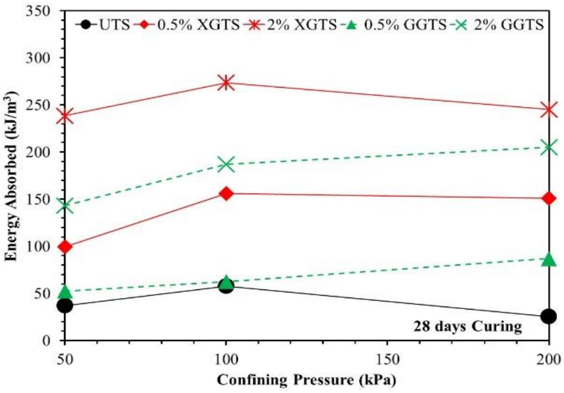


(b) GGTS

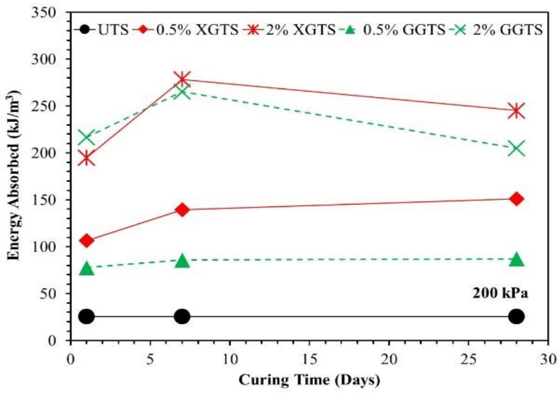
Fig. 7 Effect of biopolymer content, curing period and confining pressure on 'E'



(a) EAC for various biopolymer content

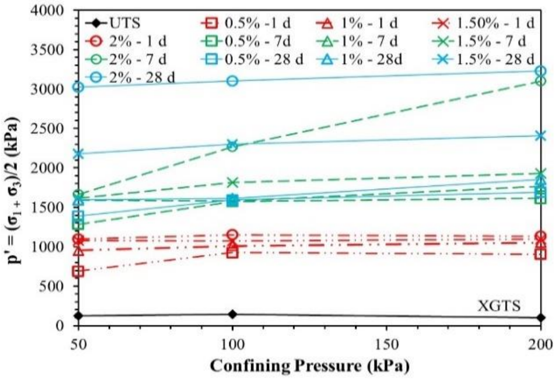


(b) EAC for various confining pressures

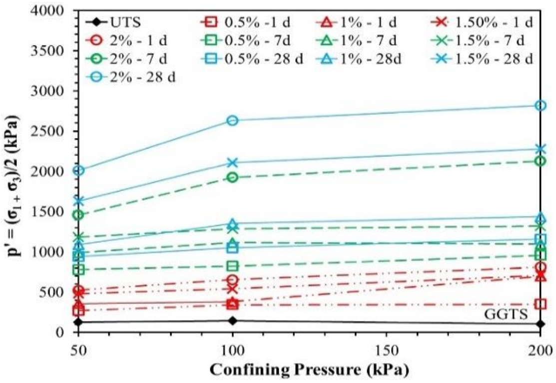


(c) EAC for various curing periods

Fig. 8 Effect of biopolymer content, confining pressure and curing period on EAC of UTS, XGTS and GGTS



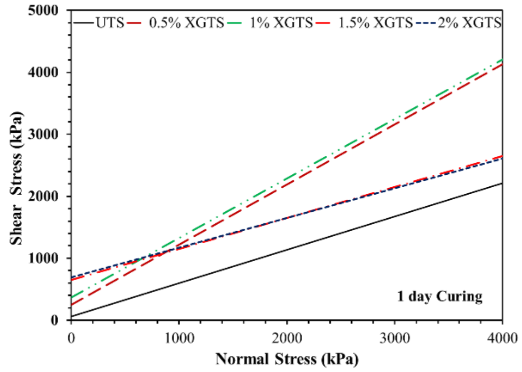
(a) XGTS



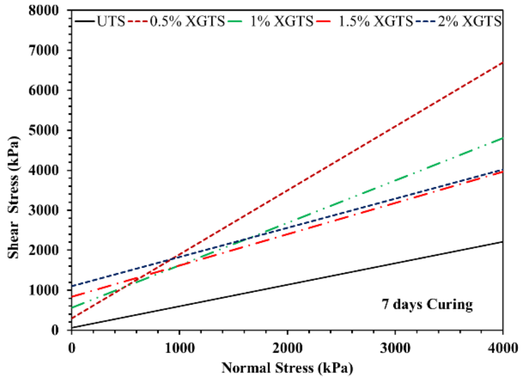
(b) GGTS

Fig. 9 Effect of confining pressure, biopolymer type, content and curing period on p'

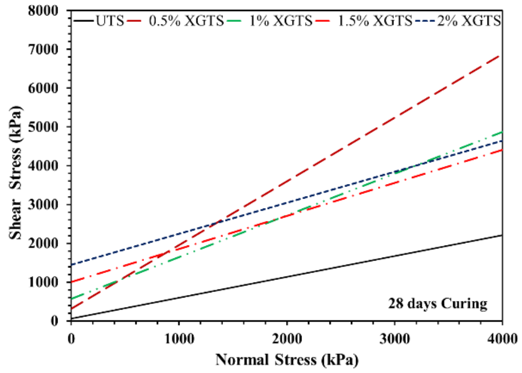
The failure strain of XGTS and GGTS is lower than the failure strain of UTS at 50 kPa irrespective of the biopolymer content, confining pressure and curing periods with the exception of 2% GGTS at 200 kPa, where it is marginally higher than that of UTS. The failure strain varies between 3.95% and 12.5% for the soil (i.e., clayey sand) at various confining pressures. It ranges between 3.29% and 9.87% in the case of XGTS and 3.29% and 13.56% for GGTS for all investigated confining pressures and curing periods. GGTS fails at a higher strain than that of XGTS. It is also observed from Figs. 4-6 that with an increase in the curing period, the change in failure strain for various confining pressures is changed appreciably, particularly in the case of XG.



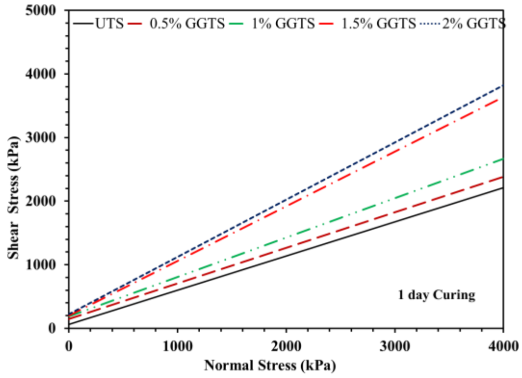
(a) XGTS - 1 day curing



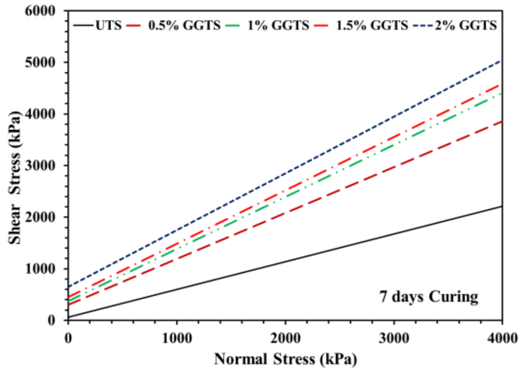
(b) XGTS - 7 days curing



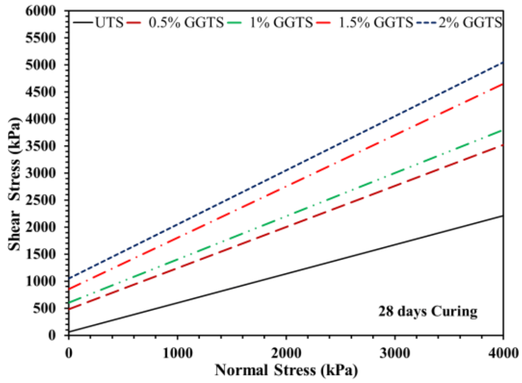
(c) XGTS - 28 days curing



(d) GGTS - 1 day curing

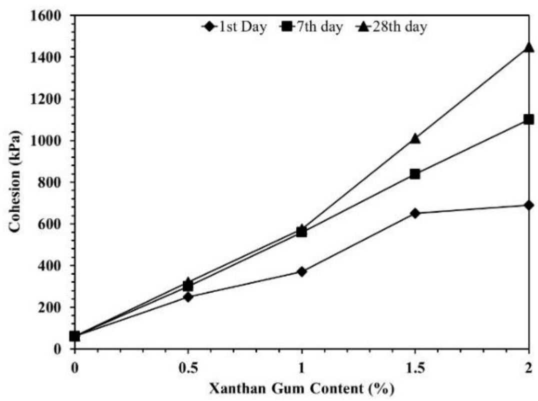


(e) GGTS – 7 day curing

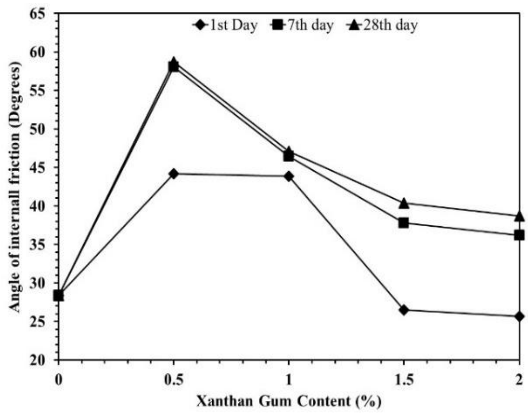


(f) GGTS – 28 days curing

Fig. 10 Mohr’s failure envelope for UTS, XGTS and GGTS at various curing periods



(a) Cohesion of XGTS



(b) Angle of internal friction of XGTS

Fig. 11 Shear parameters of UTS and XGTS

4.1.2 Deformation modulus

Deformation modulus (E) expresses the measure of soil stiffness and is defined as the fraction of the peak deviatoric stress to its corresponding strain. Figs. 7(a) and 7(b) show that the biopolymer content, type of biopolymer and curing time influences the 'E' of the soil.

Fig. 7 shows that 'E' tends to increase with the biopolymer content in general. The 'E' value of soil treated with 0.5% XG is 1.82 times lesser than that of soil treated with 2% XG after 7 days of curing at 200 kPa confining pressure (See Fig. 7). Also, at the same confining pressure and XG content, 'E' increases from 81,195 kPa to 1,01,202 kPa (i.e., 1.25 times) when the curing period increased from 7 days to 28 days.

The maximum 'E' for XGTS is attained after 7 days and there is only a nominal increase after 28 days of curing at 50 kPa confining pressure. But in the case of GGTS, there is a noticeable change in 'E' after 28 days of curing when compared to that of 7 days curing, particularly at higher percentages of GG (Fig. 7(b)) at the same confining pressure of 50 kPa. The increase in both the biopolymer content and curing period results in a high 'E'.

The XGTS exhibits higher 'E' at higher XG dosage and with an increase in curing period. The GGTS has a lesser 'E' value than XGTS at lower biopolymer content (i.e., 0.5%) but shows a marked increase at a higher dosage of 2% and higher confining pressures of 100 kPa and 200 kPa. The 'E' increased from 10287 kPa to 101202 kPa (i.e., 10 folds) and 126528 kPa (i.e., 12 folds) for soil treated with 2% XG and GG after 28 days of air curing/drying at 200 kPa confining pressure, respectively (Fig. 7).

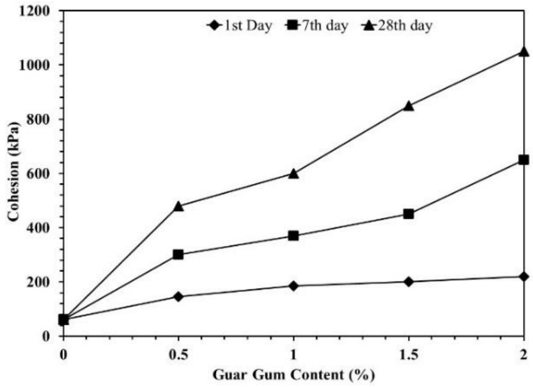
4.1.3 Energy absorption capacity

ASTM C 1018 (1997) expresses "energy absorption capacity (EAC) as the energy defined by the area under the stress-strain curve to a specified (reference) strain level." It reflects the measure of an increase in the peak stress and / or the failure strain. It is the energy required to cause deformation in a soil specimen. It depends on both the peak strength and post-peak response. EAC increases with the increase in confining pressure, biopolymer type, biopolymer dosage and curing period (Figs. 8(a), 8(b), and 8(c)). The EAC of 2% XGTS after 28 days of curing is 1.2 times higher than GGTS at the same biopolymer content and days of curing at the maximum confining pressure (Fig. 8a). EAC tends to decrease at a higher confining pressure of 200 kPa for virgin soil and XGTS at all biopolymer contents and curing periods (Fig. 8b). This decrease is more pronounced at higher biopolymer dosages. XGTS shows a higher EAC than GGTS for all the confining pressures, which is clear from their stress-strain response and Fig. 8(b). Soil treated with GG shows an increase in EAC with an increase in dosage, though the increase is marginal. For example, 2% GGTS has 3.1 times higher EAC than 0.5% GGTS after 7 days of curing and increases by 2.4 times after 28 days of curing at 200 kPa (Fig. 8(c)).

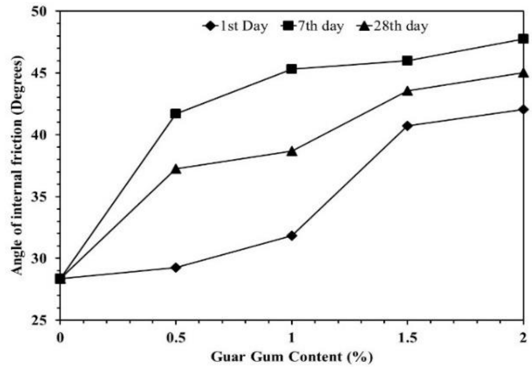
4.2 Effect of biopolymer on the strength of treated soil

4.2.1 Strength envelope

The results of the UU- triaxial test show that major



(a) Cohesion of GGTS



(b) Angle of internal friction of GGTS

Fig. 12 Shear parameters of UTS and GGTS

principal stress (p') improved with the increase in the biopolymer content for all confining pressures investigated in this study (i.e., 50 kPa, 100 kPa and 200 kPa). Figs. 9(a) and 9(b) show the impact of confining pressure, biopolymer type, content and curing period on p'. The general trend indicates a marginal increase in the p' with the increase in confining pressure, but after 7 days of curing, there is a significant increase, particularly at higher XG content (Fig. 9(a)). A similar trend is observed in the case of GGTS also but the increase is marginal for all curing periods (Fig. 9(b)) and is always less than that of XGTS.

The strength envelopes from the UU-triaxial tests for the UTS, XGTS and GGTS in Figs. 10(a) and 10(b) indicate that strength parameters – cohesion (c) and angle of internal friction (φ) show marked changes with the addition of the biopolymer. The combined effect of the shear strength parameter causes an increase in the strength of the BTS. The strength envelopes show that at all investigated biopolymer contents, curing periods, and the addition of XG causes higher 'c' to develop in the treated matrix. The maximum 'φ' value is mobilized at 0.5 % XG addition for all curing periods. GGTS shows a significant increase in 'c' value for all biopolymer contents and curing periods investigated. The 'φ' value increases with the biopolymer content but is observed to marginally decrease beyond 7 days of curing.

4.2.2 Shear strength parameters – 'c' and 'φ'

The 'c' and 'φ' values for treated soil samples were observed to be influenced by the type of biopolymer used, biopolymer dosage and curing period. The c and φ values of

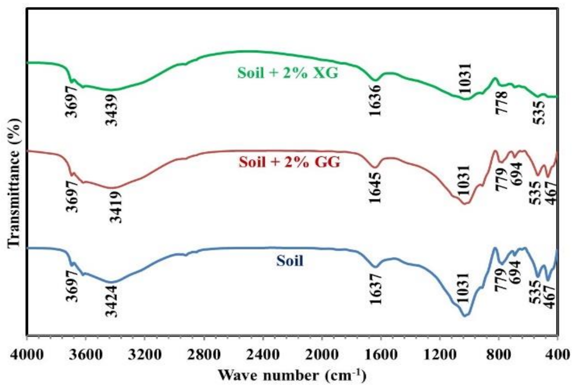
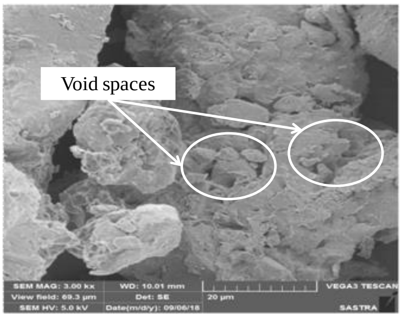
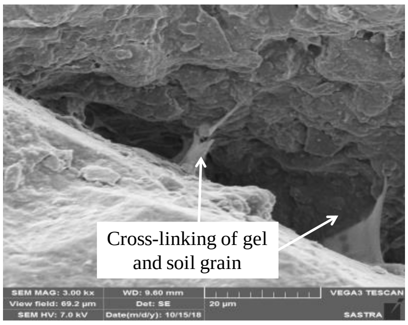


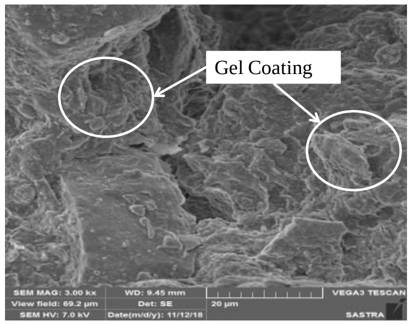
Fig. 13 FTIR pattern for UTS, 2% XGTS and 2% GGTS



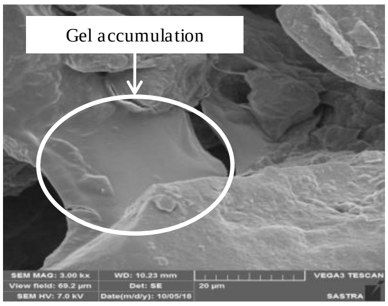
(a) UTS



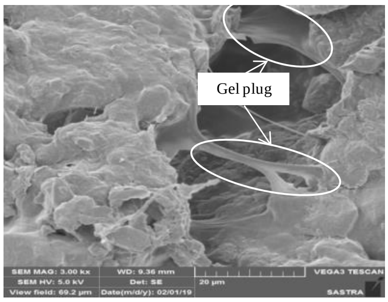
(b) 0.5% XGTS after 1 day curing



(c) 0.5% GGTS after 1 day curing



(d) 2% XGTS after 28 days curing



(e) 2% GGTS after 28 days curing

Fig. 14 SEM image showing the bio-clogging in the soil structure

the UTS, XGTS and GGTS are presented in Figs. 11 and 12. The 'c' value of XGTS showed an increasing trend, i.e., adhesion between xanthan gel and soil matrix increases with the increase in XG dosage and the days of curing to a significant extent (Fig. 11(a)). For example, 'c' value increases from 300 kPa to 1100 kPa (i.e., 3.7 times increment) with the increase in XG content from 0.5% to 2% after 7 days of curing and 690 kPa to 1450 kPa (i.e., 2.1 times increment) at 2% XG when the curing period increased from 1 day to 28 days. The maximum 'c' value is mobilized with the addition of lower dosages of 0.5% and 1% XG after 7 days of curing and does not increase markedly after 28 days of curing. But at higher dosages of 1.5% and 2% XG, a marginal increase in 'c' value is observed after 28 days of curing. GGTS shows a significant increase in 'c' value with the increase in dosage of biopolymer and days of curing (Fig. 12(a)).

Cohesion mobilized in the soil treated with 0.5% GG is 2.2 times less than that mobilized in the soil treated with 2% of GG after 7 days of curing. The 'c' value increased to 480 kPa and 1050 kPa at 0.5% and 2% of GG, resepectviely, after 28 days of curing. Cohesion mobilized by GGTS for the same dosage as that of XG is always lesser for all investigated periods of curing except at 28 days of curing, where 'c' value is higher at lower concentrations of GGTS (i.e., 0.5% and 1%), but XGTS shows greater 'c' values at higher concentrations of 1.5 % and 2 % (Figs. 11(a) and 12(a)). It can also be observed from Figs. 11(a) and 12(a) that the rate of increase in 'c' value with the increase in the curing period from 7 days to 28 days is higher for GGTS than that of XGTS.

The 'φ' value is also favorably modified by the addition of biopolymers XG and GG and is influenced by the biopolymer dosage and air-curing time. Results of this study show that at all investigated periods of curing, 0.5% XG addition has yielded the highest 'φ' value (Fig. 11(b)) and on further addition (i.e., at higher dosages of XG), the 'φ' value decreased but always remained higher than that of the UTS except in case of 1.5% and 2% XGTS after curing for a day. Also, it is observed that the maximum rate of increase is observed after 7 days of curing, but beyond the 7 days curing period, the increase in the 'φ' value is marginal. The increase in the 'φ' value with dosage is similar to that observed in the mobilization of 'c' value with the addition of XG (Fig. 11(b)).

The 'φ' value of GGTS increases for all biopolymer contents investigated (Fig. 12(b)). For example, the 'φ' value for 0.5% GGTS is 12.69% lesser than that of 2% GGTS after seven days of curing. But, the 'φ' value of GGTS is observed to decrease at longer curing periods (i.e.) 28 days. The 'φ' value of 1% GGTS decreases by 14.63% when the curing period increased from 7 days to 28 days. The rate of decrease in 'φ' value with the increasing curing period is observed to decrease with the increase in the GG content (i.e.) at 0.5% the decrease in 'φ' value is 10.65%, but on increasing the GG content to 2%, the decrease is observed to be 5.72% when the curing time extended from 7 days to 28 days. GGTS shows a higher 'φ' value than XGTS at higher biopolymer contents of 1.5% and 2% (Figs. 11(b) and 12(b)).

4.3 Effect of biopolymer treatment on molecular groups

FTIR analysis helps to identify the difference in molecular groups before and after adding the XG and GG. This analysis was carried out for the UTS, 2% GGTS and 2% XGTS and is plotted in Fig. 13 for better comparison. The spectral range of wavenumbers varied from 4000 cm^{-1} to 400 cm^{-1}. FTIR spectrum of soil shows the various absorption bands at 3696 cm^{-1}, 3424 cm^{-1}, 1637 cm^{-1}, 1031 cm^{-1}, 778 cm^{-1}, 693 cm^{-1}, 535 cm^{-1} and 467 cm^{-1}. The characteristic peaks that appeared at 3696 cm^{-1} and 1031 cm^{-1} are attributed to the presence of kaolinite and are associated with the stretching vibration of the –OH groups (Ravisankar *et al.* 2010, Smitha *et al.* 2019). The absorption bands at 3424 cm^{-1} and 467 cm^{-1} indicate the presence of montmorillonite and it may be due to the H-O-H stretching of water molecules and bending vibration of Si-O, respectively (Ahmad and Mirza 2018). The bands at 778 cm^{-1} and 693 cm^{-1} show the presence of quartz minerals due to the Si-O symmetrical stretch and symmetrical bending respectively (Ravisankar *et al.* 2010). The vibrations at 1637 cm^{-1} and 535 cm^{-1} are due to the H-O-H stretch (Smitha *et al.* 2019) and Al-O-Si Stretch (Yin *et al.* 2019).

5. Discussion

BTS shows enhanced strength and deformation behavior than UTS. A discussion on the mechanism of strength gain and favorable deformation behavior is discussed below.

5.1 Type of biopolymer

XG and GG are polysaccharides that contain functional groups like mannose, glucose, esters, hydroxyls and amines, etc. and form long-chain structures on hydration that leads to improved strength (Chang *et al.* 2015a; Ayeldeen *et al.* 2016; Latifi *et al.* 2017). The long chain-like structure of these biopolymers provides additional sites where a characteristic chemical response for a specific functional group can take place (Ayeldeen *et al.* 2016). The chemical bonding of these biopolymers through the formation of hydrogen or ionic bonds act in two ways to stiffen the soil matrix and improve its strength – (i) binds the soil particles together and (ii) links the soil matrix through gel formation (Khatami and Kelly 2013, Reddy *et al.* 2020). The strength of the bonds primarily depends on the force that exists between the gel and soil particles (Ayeldeen *et al.* 2016).

Micrographs show the biopolymer coating and formation of hydrogels that help in aggregating the particles through binding them and void plugging (Fig. 14). Also, the higher viscosity of the biopolymers used to increase the possibility of sustained crystallization of the chain of macro-molecules (Ayeldeen *et al.* 2016), which results in increased cross-linking in the treated soil matrix (Chen *et al.* 2013, Ayeldeen *et al.* 2016, Reddy *et al.* 2020). Hence, it can be rationalized that the combined effect of binding through bonds and aggregation of the soil particles lead to the strengthening of the treated soil (Chang *et al.* 2015b, Ayeldeen *et al.* 2016, Dehghan *et al.* 2019, Sujatha and Saisree 2019; Reddy *et al.* 2020).

GG contains large hydroxyl groups (Chudzikowski 1971, Chen *et al.* 2013, Alam *et al.* 2018, Sujatha and Saisree 2019) that form hydrogels. These hydrogels link the soil particles with the free water that is available through the formation of hydrogen bonds. The strength gain in soil treated with GG can be attributed to the formation of numerous hydrogel networks, hydrogen bonding and cross-linking of GG by virtue of its higher molecular weight and viscosity. Similar findings have been reported by a few researchers (Chen *et al.* 2013, Ayeldeen *et al.* 2016, Muguda *et al.* 2017, Sujatha and Saisree 2019, Reddy *et al.* 2020).

The polysaccharides in XG exhibit excellent sorption and micro-structure interaction (Reddy *et al.* 2020) as it is anionic in nature and its higher molecular weight and viscosity aids in the formation of large hydrogel networks, which help in stiffening the soil matrix. XG strongly aids cross-linking because of ionic interaction between the anionic XG and calcium cations present in the clayey sand. Also, its higher molecular weight aids better aggregation of the soil particles when compared to GG. Also, the five-fold helical structure of XG molecules offers more sites for chemical responses when compared to the two-fold helical shape of GG (Casas *et al.* 2000, Nugent *et al.* 2009, Reddy *et al.* 2020). This also affects the shear-thinning behavior of the biopolymer solutions, which in turn affects the strength of the treated soil. The anionic nature of XG leads to higher interaction and better bonding than the non-ionic GG and hence, the XGTS yield higher strength than that of GGTS.

Hydrogels formed by the addition of XG are ionic bonds that are stronger compared to hydrogen bonds formed by GG addition which results in the higher strength of XGTS (Ayeldeen *et al.* 2016, Lee *et al.* 2017, 2019, Muguda *et al.* 2017). Micrographs from SEM (Figs. 14(d) and 14(e)) confirm the higher aggregation of XGTS than GGTS, resulting in higher strength of the soil treated with XG. The same reason can be attributed to the changes in deformation behavior like peak stress, 'E' value and EAC between

GGTS and XGTS.

5.2 Biopolymer dosage

Strength of the soil treated with biopolymer increases remarkably with the biopolymer content for both the biopolymers investigated, though the rate of increase in strength is dependent on the biopolymer type. An increase in the biopolymer concentration also leads to an increase in the 'E' of the treated soil. The micrographs (Figs. 14(b) to 14(e)) demonstrate the accumulation of biopolymer that creates the linkages in the pore-spaces of the treated soil increases with the biopolymer content. Comparison of Figs. 14d and 14e show that wide and thick linkages are created by XG treatment than those of GGTS which explains the higher strength of XGTS with the increase in the dosage (Ayeldeen *et al.* 2016, Latifi *et al.* 2017, Muguda *et al.* 2017). The viscosity of the biopolymer solutions increases with the increase in biopolymer content (Table 3).

At lower biopolymer content (i.e., 0.5 %), both XG and GG solutions behave as Newtonian fluids by virtue of their lower viscosity but at higher dosages behave as non-Newtonian and thixotropic systems (Ganal El-Awad El-daw 1998; Reddy *et al.* 2020). Both the biopolymers – XG and GG exhibit strong shear thinning behavior owing to the stiffness of the molecules and intermolecular association of the molecules with the increase in the biopolymer content (Cano-Barrita and Leon-Martinez 2016, Reddy *et al.* 2020). Also, high biopolymer content has a greater affinity for water and retains a large quantity of water, i.e., higher biopolymer content has greater water demand and greater viscosity which leads to higher particle aggregation (Chen *et al.* 2013, Das *et al.* 2015, Cabalar *et al.* 2017) as its higher viscosity the biopolymer tends to hold the soil particles together. XG has a higher viscosity than GG and thereby greater water demand at all dosages and hence yields higher strength and stiffness than the GGTS. Authors (Chang *et al.* 2015b, Cabalar *et al.* 2017, Reddy *et al.* 2020) suggest that the specific surface area of XG is higher and can lead to higher interactions among the soil particles in the treated matrix, thereby increasing the strength of the XGTS matrix.

5.3 Curing period

The increased strength of the treated soil with time can be attributed to the dehydration of the water imbibed by the gel formed in the soil matrix. This creates stiff cross-linkers (compounds that are formed between polymer strands) to be formed in treated soil that connects the particles in the soil matrix and results in a stiffer soil matrix (Nugent *et al.* 2009). Viscosity is a function of both dosage and time (Cabalar *et al.* 2017) and their increase with time can be attributed to improvement in strength at lower dosages as the curing period increases (Reddy *et al.* 2020).

Hydrogels in a GGTS matrix transforms to a glassy state approximately after 7 days of curing (Ayeldeen *et al.* 2016, Muguda *et al.* 2017) that leads to an increase in the strength and stiffness of the hydrogel network with the treated soil matrix leading to an increase in strength of the treated soil. In the case of XGTS, the strengthening of the ionic bonds with time leads to an increase in the strength of the treated soil. Few authors reported in their studies that the ionic bonds and the glassy phases are permanent in nature and hence the binding or the bridging of the soil particles can also be expected to be permanent (Muguda *et al.* 2017; Reddy *et al.* 2020). The study also shows that the strength and stiffness of the soil treated for both the biopolymers – XG and GG keep increasing with the increase in the curing period. The possible alteration in the hydrogels formed, such as gel hardening due to aging, can be attributed to the long-term increase in strength (Dehghan *et al.* 2019).

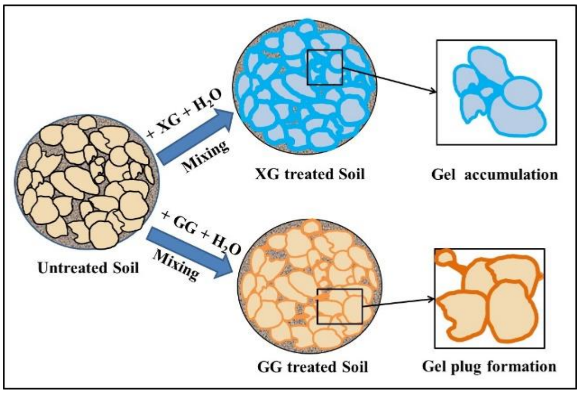


Fig. 15 Strengthening mechanism of XGTS and GGTS

The strength and stiffness of the treated soil have been improved with the increase in biopolymer content and curing period, as seen in Figs. 3-5, 7(a) and 7(b). This can be attributed to the fact that with the increase in biopolymer content, the time required for the interaction of the biopolymers in the soil matrix and formation of the products of hydration requires more time to maximize the strength of the soil-biopolymer mixtures (Dehghan *et al.* 2019, Soldo and Miletić 2019, Sujatha *et al.* 2020).

5.4. Mechanism of strength gain

Previous studies show that the xanthan gum is more effective in clay than sand (Chang *et al.* 2015b). But in this study, the soil contains both sand and clay particles. When compared to that of soil, the biopolymers have a high specific surface with more active electric charges which are ready to interact with the soil. Because of the presence of (-COOH) and (-OH) groups in the xanthan structure, it tends to directly interact with the electric charges present in the clay particles and form the ionic and hydrogen bonding (Chang *et al.* 2015b, Latifi *et al.* 2017, Muguda *et al.* 2017). The XG and the clay matrix will act as a cementitious gel between the coarse particles and thus enhance the shear strength (Chang *et al.* 2015b, Latifi *et al.* 2017, Muguda *et al.* 2017). The shear strength of the GGTS is comparatively less because the GG is non-ionic in nature.

The SEM images, Figs. 14(b) to 14(e) show the differences between XG and GG treated soil at comparable dosages and curing periods. The surface of soil particles and void spaces of the XGTS were coated with the cementitious gel and the interconnection between the particles appears very strong. But in the case of the GGTS, the thickness of the gel plug is comparatively lesser. Soldo *et al.* (2020)

Table 5 Ultimate bearing capacity of BTS

BC (%)	Ultimate bearing capacity q_u (MPa)					
	XGTS			GGTS		
	1 day	7 days	28 days	1 day	7 days	28 days
0	3.2					
0.5	142.5	280.4	307.5	7.2	50.7	48.3
1	79.1	170.2	193.5	11.5	94.0	68.7
1.5	24.7	88.0	136	30.3	128.6	136.4
2	24.3	131	174.6	39.6	237.5	241.2

* BC – Biopolymer content

Table 6 Cost comparison

Stabilizer	Content (%)	Mass of soil (Tonne)	Mass of additive needed (tonne)	Cost per tonne (Rs.)	Total cost in Lakhs (Rs.)
XG	0.50	192.17	0.97	235000*	2.27
GG	2	189.27	3.86	143000*	5.52

* Rate of the cement and biopolymers were obtained from the India Mart Website

reported the superiority of the XGTS over the other BTS and pointed out that the presence of XG links and the aggregation of soil particles in XGTS resulted in higher strength. GG enhances the soil strength for soil types like the well-graded sand with silt. This strengthening mechanism is clearly shown in Fig. 15.

As the curing time increases, the water in the soil matrix dries, leading to an increase in the strength due to dehydration of the hydrogels. By increasing the biopolymer content, the biopolymer and the soil tend to take a longer period for the cation exchange between the xanthan, water and the soil particles resulting in further increased shear strength.

5.5 FTIR

Fig. 13 shows that for the 2% XGTS, there is a forward shift of absorption band from 3424 cm^{-1} to 3439 cm^{-1} and the peaks at 693 cm^{-1} and 467 cm^{-1} seem to be absent. Likewise, for 2% GGTS, there is a backward shift of absorption band from 3424 cm^{-1} to 3418 cm^{-1} and a slight forward shift from 1637 cm^{-1} to 1644 cm^{-1}. All other absorption bands were present in the treated soil also. From the FTIR results, it is very clear that there is a variation in the observed spectra before and after treatment with the biopolymers. This is attributed to the formation of new molecular bonds between the biopolymer and the soil, which leads to strength enhancement (Smitha *et al.* 2019). The same behavior was also observed by Smitha *et al.* (2019) on using a similar gel-type biopolymer called agar.

5.6 Comparison with previous studies

The results of the present study concur with the results reported by Dehghan *et al.* (2019) and Soldo and Miletic (2019) using biopolymers XG and GG on soils of type silty sand and sandy lean clay. XGTS showed better performance than GGTS in this study also. Soldo *et al.* (2020) also report that XGTS showed superior behavior than soil treated with GG, β-glucan, chitosan and alginate in a similar type of soil – well graded sand with silt (SW-SM). The improvement of shear strength parameters – c and φ in the case of GGTS are in agreement with the results reported by authors Ayeldeen *et al.* (2017) and Dehghan *et al.* (2019). This study also concludes that XG shows superior behavior than GG and this can be attributed to its anionic nature (Chang *et al.* 2016, Dehghan *et al.* 2019, Soldo *et al.* 2020) that helps to develop stronger bonds.

5.7 Practical geotechnical application

The ultimate bearing capacity of the soil is calculated using Terzaghi's bearing capacity theory (Lee *et al.* 2019) for UTS and soil treated with biopolymers, XG and GG. A square footing of size 1 m x 1 m, placed at a depth of 1 m, is considered for the study. The ultimate bearing capacity (q_u) is given as

$$q_u = 1.3\ cN_c + \gamma\ (DN_q + 0.4\ BN_\gamma) \quad (1)$$

where c= cohesion of soil, γ = unit weight of the soil, D = depth of footing, B = width of footing, and Nc, Nq and Nγ are the Terzaghi's bearing capacity factors which depend on φ.

The q_u of the soil is influenced by both biopolymer content and the curing period. The q_u of the treated soil at 0.5% XG and GG dosage is 45 and 2.3 times higher than that of the UTS, respectively, after 1-day curing period. Table 5 shows that the q_u of the soil at 0.5% XG dosage is the maximum for all investigated xanthan contents and decreases with a further increase in XG content. The q_u of the XGTS increases as the curing period increases for all the dosages investigated.

The q_u also increases with the increase in GG content (Table 5) for all dosages investigated. But tends to decrease after 28 days of curing at lower dosages of 0.5% and 1%. It also shows a very marginal increase at higher dosages of 1.5% and 2%. At higher GG dosages and an increased curing period, the q_u is observed to be equal or marginally higher than that of XGTS (Table 5).

5.8 Economic feasibility

Results from Table 5 indicate that the optimum biopolymer content is 0.5% in the case of XGTS and 2% for GGTS. An increase of nearly 97 folds and 150 folds in q_u is observed for XG and GG, respectively, at their optimum biopolymer content. Therefore, a comparison is drawn between the cost of soil treated with 0.5% XG and 2% GG. Consider a 10 m x 10 m x 1m trench of the soil of unit weight 18.94 kN/m^3 that needs to be stabilized. Table 6 shows the cost comparison between the XG and GG stabilization of the aforementioned soil.

Biopolymers are costlier than conventional stabilizers, due to increased cost that can be attributed to lesser production in the current scenario, but the impetus to use biopolymers in soil stabilization will increase their demand which in turn can lead to the increase in production , thereby reducing costs. Also, the inclusion of carbon taxes involved in the manufacture of conventional additives like cement (Ayeldeen *et al.* 2016, Chang *et al.* 2016a) will render biopolymer stabilization not only a sustainable alternative but also as an eco-friendly and more economical option.

6. Conclusions

The results of the study on treating the clayey sand with the biopolymers XG and GG point to the following conclusions.

i. The deviatoric stress and the 'c' value increased by 16 and 23 folds for 2% XGTS and 11.5 and 17 folds for the 2% GGTS respectively, after 28 days of air-curing.

ii. The maximum increase in the 'φ' value was observed at 0.5% concentration of XG (i.e., 2 folds increment) after 28 days of curing but showed a reduction on increasing the XG content further. The increase in the 'φ' value was 1.5 folds at a 2% concentration of GG after a curing period of one day.

iii. The 'E' at failure corresponding to the maximum deviatoric stress is enhanced by 10 folds and 12 folds when the soil is treated with 2% of xanthan and GG respectively, underlining the significant increase in stiffness of BTS.

iv. The EAC under static conditions increased by 10 folds and 8 folds in the case of 2% XGTS and 2% GGTS respectively, at the maximum confining pressure and curing period investigated reflecting the increase in the peak deviatoric stress.

v. The q_u of XGTS at 0.5% XG increased by 97 folds compared to that of UTS. But GGTS showed an increase of 76 folds at 2% GG addition.

vi. The cost for stabilizing the soil with 0.5% XG is 2.4 times lower than that of stabilizing it with 2% GG.But encouraging the large-scale production of biopolymers can bring down the price and thereby enable a cost-effective solution.

vii. Micrographs from SEM and results of FTIR analysis demonstrate that the strength gain can be attributed to the void plugging mechanism and change in functional groups of BTS.

viii. Based on the results of the shear strength parameter – c and φ and the q_u of the UTS and BTS, the optimum dosage of the XGTS and GGTS is found to be 0.5% and 2%, respectively.

ix. Both the XG and GG show promising improvement in the mechanical properties of clayey sand at various biopolymer contents and curing periods investigated. Though, XGTS is observed to be superior to GGTS.

The results of the study strongly suggest that both XG and GG can be used for soil stabilization. Also, biopolymers like XG and GG can also be used as additives in the manufacture of earth blocks as they improve the strength of the treated soil considerably. It will be a step further toward sustainable development. Further investigation on strength for the extended curing periods beyond 28 days under various drainage conditions and the effect of extreme environmental conditions (i.e., elevated temperatures, wet-dry & freeze-thaw cycle and complete saturation) on the BTS is suggested for a deeper understanding of the suitability of these biopolymers under various practical applications in geotechnical engineering.

Acknowledgments

This work was supported by the TRR fund [TRR18] from the SASTRA Deemed University, Thanjavur, 613401, Tamil Nadu, India. The authors thank the Vice-Chancellor of SASTRA for the support and infrastructure provided during the period of the study.

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