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ORIGINAL PAPER

Enhancing the geotechnical properties of soil using xanthan gum—an eco-friendly alternative to traditional stabilizers

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Abstract
Several soil stabilization techniques have been adopted to favorably modify the geotechnical properties like hydraulic conductivity, strength, and compressibility of soil. In this study, xanthan gum (XG), an anionic bacterial extracellular polysaccharide is used to modify the geotechnical properties of the soil, particularly its strength and hydraulic conductivity. The addition of xanthan gum to soil improves its strength and stiffness and also decreases its hydraulic conductivity. The addition of xanthan gum induces polymer cross-linking, forms interconnected network of hydrogels in the voids of the soil matrix and causes preferential adsorption of the biopolymer molecules and cations on the soil surface. These interactions between the soil and the biopolymer alter the geotechnical properties of the treated soil matrix favorably. The decrease in permeability is nearly 1000 times with a small addition of 0.25% xanthan gum to the soil. Xanthan gum tends to aggregate the particles at lower concentration and at higher concentrations forms more viscous hydrogels that fill the pore spaces and clogs the pores. Strength also shows a similar increase and hence xanthan gum can be recommended for soil stabilization.

Keywords Xanthan gum · Unconfined compressive strength · Permeability · Bio-clogging · Viscosity · Hydrogels

Introduction

Traditional chemical admixtures like lime, cement, bituminous materials, fly ash, calcium, and carbide are most commonly used for construction purposes. Though these admixtures provide multiple benefits like high strength, improved durability, hydraulicity, and workability at reasonable cost (Chang et al. 2016), they leave a permanent and irreversible mark on the environment. For example, cement, a widely used popular soil stabilizer liberates 0.55 t of carbon dioxide for every tonne of cement produced (Latifi et al. 2016). Cement by itself contributes to nearly 5% of global production of carbon dioxide (Chang et al. 2016). Dust from the particulate emissions cause serious environmental concern (Dash and Hussain 2012; Thangaraj and Thenmozhi 2013; Chang et al. 2016; Latifi et al. 2016). In addition to carbon dioxide, nitrogen oxides are also produced in the cement kilns during the manufacture of cement. Traditional admixtures alter the pH of the treated soil affecting the vegetation and quality of the ground water and lead to desertification. Also, authors like Chang et al. (2015) and Latifi et al. (2016) report that soil treated with traditional admixtures like lime and cement exhibit brittle nature that adversely affects the stability of the structures.

Environmental concerns and need for sustainable development demand an environment-friendly stabilization technique. Numerous non-traditional alternatives like resins, acids, enzymes, silicates, lignin derivatives, and biopolymers are available to be used as soil admixtures (Blanck et al. 2014; Latifi et al. 2015; Chang et al. 2016). These materials either occur naturally or can be manufactured by natural processes. Biopolymers like chitosan, sodium alginate, beta glucan, and xanthan can replace traditional admixtures as soil additives (DeJong et al. 2011; Chang and Cho 2012; Chen et al. 2013; Latifi et al. 2016; Ayeldeen et al. 2017; Kwon et al. 2019) and find applications in bioremediation, liquefaction mitigation, erosion control, slope stabilization, stabilization of collapsible soil, and soil strengthening. Biological methods provide a sustainable and environment friendly substitute to enhance the index and engineering properties of the soil. Biological methods broadly include microbial injection and by-product

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precipitation (Chang et al. 2016). Biopolymers are carbon neutral, sustainable, and renewable resource as they are derived from natural sources and hence have emerged as a new construction binder for ground improvement.

Recent researches show that biopolymers are effective in lowering the permeability of the soil through bio-clogging (Martin et al. 1996; Khachatoorian et al. 2003; Ivanov and Chu 2008; Bouazza et al. 2009; Cabalar et al. 2017) and improve the strength through bio-cementation (Khachatoorian et al. 2003; Chang et al. 2015; Latifi et al. 2016; Kwon et al. 2019). Chang et al. (2015) report in their study that strength of xanthan gum-treated soil increases with gum content but levels off at higher concentration. The success of the effect of the biopolymer on the soil depends on the type of biopolymer, nature of soil, biopolymer content, curing time and conditions, and method of mixing (Ayeldeen et al. 2016). Though the results of the studies are encouraging, there is still reluctance to extend their application in the field. This lack of acceptance can be attributed to lack of standard procedures for sample preparation and testing, methods for evaluating field performance, inadequate information about the manufactured biopolymer, biological degradation, durability of the biopolymer-treated soil, market costs and sensitivity to water, etc. (Tingle and Santoni 2003; Chang et al. 2016; Ayeldeen et al. 2017). Despite these limitations, there is more scopes for the utilization of biopolymers like xanthan gum, guar gum, and gellan gum in various geotechnical engineering applications but this requires extensive research on the mechanism of biopolymer strengthening the soil and study on the performance of biopolymer-treated soil for long periods of curing. These results are very sparingly reported in literature and hence needs an in-depth research.

An attempt has been made to understand the effect of xanthan gum, an anionic biopolymer derived from the bacteria *Xanthomonas campestris* on sandy clay. It is extensively used in the food, oil, and agriculture industry as a thickener and is a rheological modifier. The engineering behavior of the xanthan gum-treated soil at various percentages and different curing periods was investigated. The geotechnical properties of the soil-xanthan gum blend like consistency limits and indices, compaction characteristics, permeability, and unconfined compressive strength were studied. Long-term behavior of the soil-xanthan blends were also evaluated for a period of 90 days under air curing. The mechanism of biopolymer modification of the soil was examined with micro-structure analysis and surface analysis of the treated samples.

Materials and methods

Soil

Soil was excavated from Srirangam near Thiruchirappalli, Tamil Nadu from a trench 1.5 m below the ground level to avoid the topsoil. Soil is brown in color and does not exhibit pungent odor. The organic content of the soil was less than 1%. X-Ray fluorescence analysis of the soil shows that it has 60.51% silica, 19.6% alumina, 8.94% ferrous oxide, 3.39% calcium oxide, 2.2% potassium oxide, 2.11% magnesium oxide, 1.12% titanium oxide, 1.05% sodium oxide, and oxides like phosphorous pentoxide, lead oxide, and barium oxide less than 1%. X-Ray diffraction analysis reveals the presence of kaolinite, dickite, palygorskite, sepiolite, allophane, imogolite, and pargasite. The soil contains 1.15% gravel, 58.85% sand, and 40% fines comprising of silt and clay. The effective diameter of the particle is 1.37 μm. The soil properties are presented in Table 1. It is a coarse-grained soil; the clay present in the soil matrix has high plasticity and low shrinkage index indicating that it is less susceptible to volume change. Also, its liquid limit indicates that the clay content present in the soil matrix is less compressible in nature. The hydraulic conductivity of the soil is high. The soil has a lower optimum moisture content indicating that is granular in nature.

Xanthan gum

Xanthan gum, an exocellular polysaccharide derived from fermenting glucose or sucrose consists of five sugar residues—namely glucose (two), mannose (two), and glucuronic acid (one) that occur as repeating units (Melton et al. 1976; Tran et al. 2017). The trisaccharide chain aligned with the b-D glucone backbone provides stability. It is pseudo plastic, and a small amount of xanthan gum can considerably increase the viscosity of water considerably. It is stable over a wide range of pH and temperature (Chang et al. 2015). It is anionic and hydrophilic in nature. It is commonly used to thicken drilling fluids in order to improve the drilling efficiency (Chang et al. 2015). It also finds application as an additive to prevent washouts in concrete as it enhances the viscosity (Plank 2004; Comba and Sethi 2009; Latifi et al. 2016).

Experimental investigation

Soil was collected from the site, and was oven dried after pulverization at temperatures between 100 and 105 °C. Xanthan gum was dry-mixed with soil in proportions of 0.25, 0.5, 0.75, 1, 1.25, 1.5, 2, 3, and 5% to the dry weight of soil and hand mixed thoroughly (Bouazza et al. 2009; Chang et al. 2015). Two percent of water of the dry weight of soil was added to the soil and was allowed to reach the equilibrium moisture for the light compaction test (Ayeldeen et al. 2016). The soil samples were prepared using the procedure outlined by Bouazza et al. (2009) for the hydraulic conductivity test. Soil samples were mixed with biopolymer in the required quantity at the optimum moisture content (OMC) and

Table 1 Characteristics of soil

Geotechnical property	Values	Geotechnical property	Values
Specific gravity	2.28	Shrinkage index	4.89
Liquid limit (%)	38	Soil classification	Clayey sand
Shrinkage limit (%)	14.8	Optimum moisture content (%)	10
Plasticity index	18.9	Maximum dry unit weight (kN/m^3)	19.33
Flow index	22.9	Hydraulic conductivity (cm/s)	10.28×10^{-3}

were preserved in airtight containers for 12 h. Then it was compacted at light compaction energy and saturated completely. The experimental investigation to determine the liquid, plastic and shrinkage limit, light compaction, hydraulic conductivity, and unconfined compressive strength of the soil was carried out according to the procedures outlined in ASTM D4318, ASTM D427, ASTM D698, ASTM D5856, and ASTM D2166 respectively. Soil was compacted into cylinders, 38 mm in diameter, and 76 mm height at their respective OMC for the unconfined compression test. Soil and xanthan gum were initially dry mixed the soil with a minimum 2% water content, then the remaining water was added and thoroughly hand mixed to attain a homogenous mixture and was then compacted.

Results and discussion

The addition of xanthan gum, an anionic biopolymer interacts with the soil in the following ways: (i) aggregating of soil particles, (ii) cross-linking of polymers by divalent cations, (iii) forming interconnected soil-biopolymer network through hydrogen bonds and cation bridging, (iv) change in double-layer thickness (due to the presence of different types of cations in different concentrations), and (v) preferential adsorption of biopolymer molecules and cations on the soil surface, particularly clay (Chang et al. 2015; Kwon et al. 2019). These interactions between the soil and the biopolymer can amend the geotechnical properties of the soil matrix treated with xanthan gum.

Index properties

Liquid limit (LL) represents the fluid (water) content necessary to decrease the soil's shear strength below a specific minimum threshold. It reflects the interaction at microstructural level and particle level of the soil. The viscous nature of xanthan gum contributes to increase in liquid limit as the xanthan-soil matrix contributes to shear resistance. Liquid limit tends to increase with the addition of xanthan gum. The rate of increase in LL increases with the gum content and is a function of the viscosity of the xanthan gum solution (Nugent et al. 2009). A higher quantity of xanthan gum causes the viscosity of the pore fluid to increase and thereby increases the LL of the soil. Formation of hydrogel in the pore spaces of the soil matrix and the electrical interaction between the clay particles in the soil and xanthan gum also lead to the increase in liquid limit (Kwon et al. 2019). The maximum liquid limit of 57% is observed at 5% xanthan gum (Fig. 1). The presence of kaolinite in the soil promotes anionic xanthan gum molecules to link with the adsorbed cations (Nugent et al. 2009). It is also to be noted that kaolinite has limited capacity for cation exchange with a net negative charge limiting the degree of linking. The strands of xanthan gum provide a mechanism for aggregation by binding the soil particles together. The tendency of the soil particles to aggregate in the presence of xanthan gum causes the change in the liquid limit. When the xanthan gum content is less, aggregation has more influence on the liquid limit as the pore fluid's viscosity is less. The presence of kaolinite as clay mineral in sandy clay has limited influence on liquid limit at high xanthan gum content owing to the greater viscosity of pore fluid.

The linear increase in LL of xanthan gum-treated soils can be ascribed to the hydrophyllic nature of the biopolymer. The liquid limit of the xanthan gum-treated soil can be approximated given as:

$$\text{Liquid limit of the xanthan-gum-treated soil } (\%) = 5.98\ (\text{xanthan gum content in}\%) + 37.76 \quad (1)$$

Plastic limit (PI) shows a marginal increase with the addition of xanthan gum for all percentages of xanthan gum investigated. Addition of xanthan gum leads to increase in the viscosity of the pore fluid and thereby causes higher aggregation in the soil matrix. The plasticity index of the xanthan gum-treated soil is also observed to increase with xanthan gum content. The percentage increase in the PI of the 5% xanthan gum-treated soil is nearly 30%. A similar linear trend of increase as in the case of liquid limit is also observed for plasticity index of the xanthan gum-treated soil. The approximate equation that relates the PI of the treated soil with the xanthan gum content is:

$$\text{PI of the xanthan gum treated soil } (\%) = 2.28\ (\text{Xanthan Gum in}\%) + 20.02 \quad (2)$$

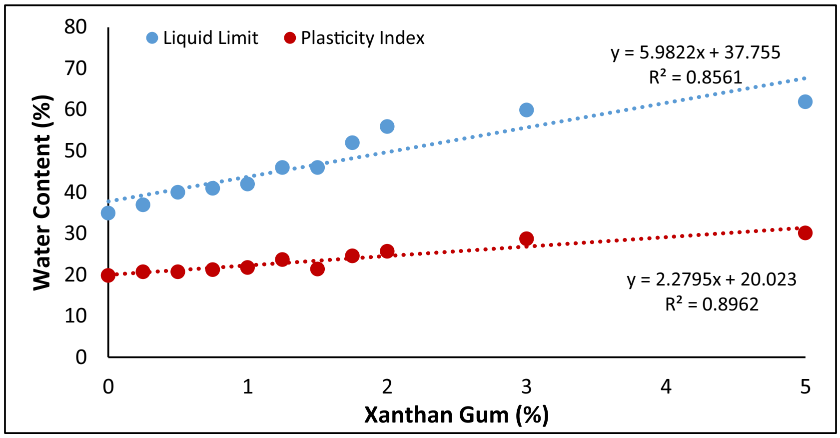

Fig. 1 Liquid limit and plasticity index of xanthan gum-treated soil

The rise in LL and PI of the treated soil also indicates a slight shift in the classification of the soil. The soil shifts from low compressible clay at xanthan gum concentrations lower than 2% to highly compressible clay at higher concentration of 2% and above (Table 2) according to the Unified Soil Classification System. Authors like Kwon et al. (2019) have also reported such change in classification of soil on addition of xanthan gum. Shrinkage limit of the treated soil samples decreases when the xanthan gum content is lower than 1.5% but increases significantly at higher concentrations beyond 1.5%. At lower xanthan gum content, pore fluid's viscosity is low and therefore the formation of the interconnected network through cation bridging and hydrogen bonds is less (Nugent et al. 2009) and hence the susceptibility to volume change on drying is also less but at higher concentration, the soil-biopolymer matrix is stiffer and the viscous nature of the pore fluid causes greater drying (Kwon et al. 2019). Also, the dehydration caused by condensation of biopolymer hydrogels (Chang et al. 2016) could have caused the marked change in shrinkage limit.

Compaction characteristics

Soil density is an important parameter in the control of many construction projects like roads, airfields, embankments, earth wall, and earthen dams. It influences the mechanical properties of the soil like its coefficient of permeability, shear strength, bearing capacity, and settlement rate (Chang et al. 2015; Ayeldeen et al. 2016, 2017). Therefore, this study investigated the effect of biopolymer on the compaction characteristics of the treated soil.

Results of the experimental investigation reveal that change in dry unit weight with increase in water content is marginal as the xanthan gum content increases (Fig. 2) compared to that of soil that is untreated. The compaction curves tend to get flatter on treatment with xanthan gum. This points to the fact that xanthan gum renders the soil less sensitive to moisture changes. This tendency is pronounced at higher percentages of xanthan gum addition (Fig. 2) and can be attributed to the formation of interconnecting network of hydrogen bonds and cross-links that render the soil matrix stiffer and resist compactive effort (Chang et al. 2015; Ayeldeen et al. 2016; Kwon et al. 2019). The higher viscosity of the pore fluid with increase in XG content also contributes to the resistance offered by the soil matrix against compactive effort. This provides an advantage in the field as the dry unit weight does not vary significantly over a wide range of water content, and the placement water content can be selected with a large margin.

Figure 2 also shows that up to 2% addition of xanthan gum the changes in dry unit weight are marginal and do not show a definite trend but beyond 2% there is a definite decreasing trend. The nature of the compaction curves indicates the change in the structural arrangement of the soil particles. At low concentration of xanthan gum, the interaction between the

Table 2 Index properties and classification of axnthan gum-treated soils

Index property	Soil	Xanthan gum (%)									
		0.25	0.5	0.75	1	1.25	1.5	1.75	2	3	5
Liquid limit (%)	35	37	40	41	42	46	46	48	52	55	57
Plastic limit (%)	15.1	16.2	19.2	19.7	20.2	25.3	25.6	27.4	30.3	31.2	31.8
Plasticity index (%)	19.9	20.8	20.8	21.3	21.8	20.7	20.4	20.6	21.7	23.8	25.2
Shrinkage limit (%)	14.8	6.35	10.25	10.75	11.97	13.98	14.02	20.53	21.53	33.15	42.17
Soil classification	SC	CL	CL	CL	CL	CL	CL	CL	CH	CH	CH

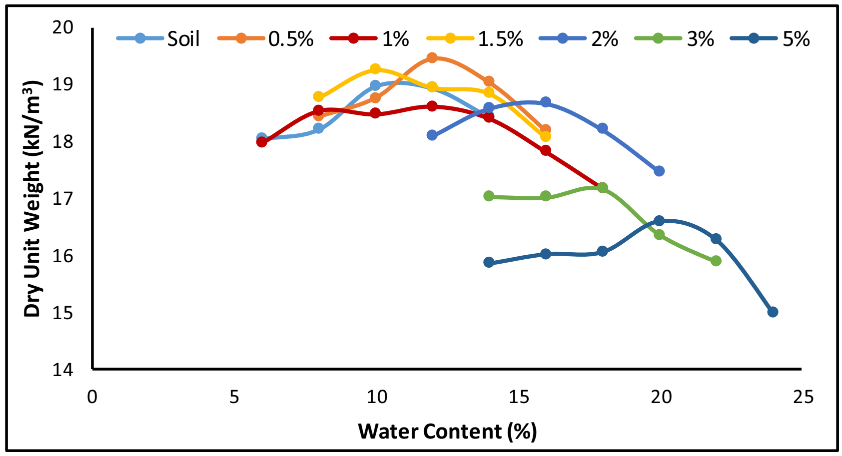

Fig. 2 Compaction characteristics of xanthan gum-treated soil

soil particles is predominant and the formation of hydrogels is not very pronounced as observed from Fig. 3a (i). The low viscosity of the pore fluid at lower xanthan gum concentration does not inhibit the inter-particle interaction and thereby the structure may be flocculated. But with the increase in concentration of xanthan gum, the viscosity of the pore fluid increases many folds and inhibits the inter-particle interaction. The soil matrix at 5% xanthan gum as seen from Fig. 3a (ii) shows dense coating and formation of hydrogels in the pores of the soil matrix and this can be the reason for resistance to compaction at the higher biopolymer contents resulting in flatter compaction curves.

The maximum dry unit weight increases marginally from 18.98 to 19.45 kN/m^3 at 0.5% XG addition (Fig. 3b). The tendency of the xanthan gum to aggregate soil particles causes this marginal increase in dry unit weight (Fig. 3a (i)). Also, at a low concentration of 0.5%, viscosity of the pore fluid is much lower (i.e.) 359 cps and increases non-linearly with increase in

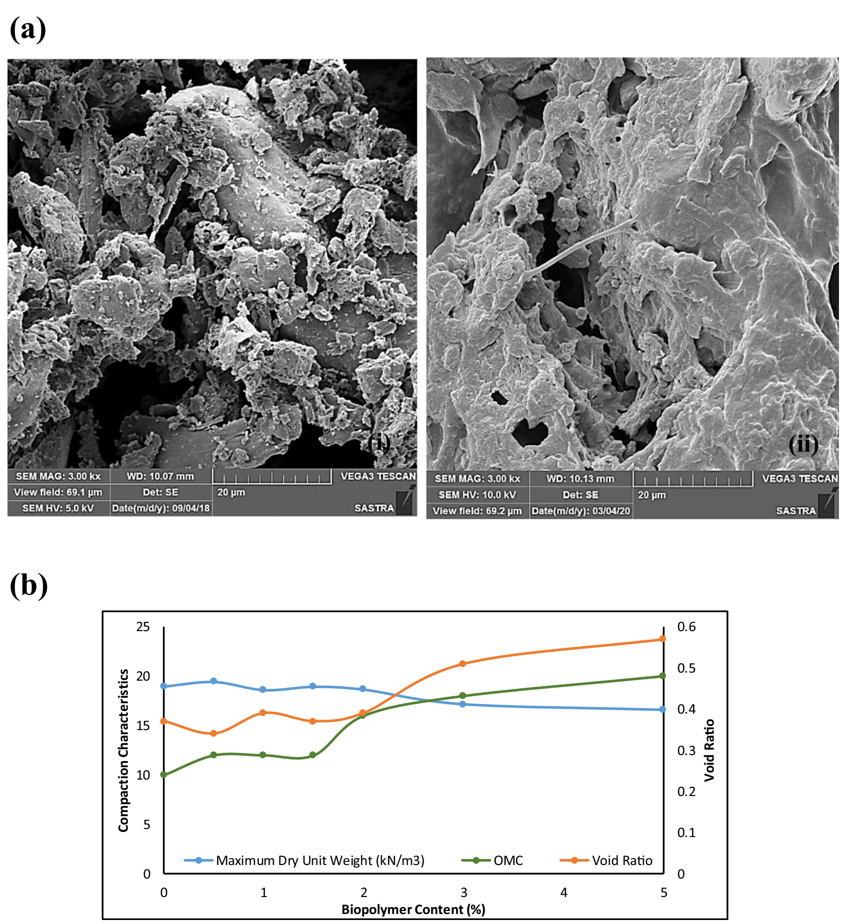

Fig. 3 **a** Soil particles showing (i) inter-particle interaction at 0.25% xanthan gum and (ii) higher bonding due to formation of hydrogels at 5% xanthan gum. **b** Effect of xanthan gum content on compaction characteristics

concentration of XG (Table 3), at 3% concentration, the viscosity is 4100 cps. At 5% concentration forms a thick gel.

At higher concentrations, the maximum dry unit weight gradually reduces and shows a significant reduction at 3% addition of xanthan gum. The significant increase in viscosity of pore fluid at higher concentrations leads to lesser dry unit weight. Also, an increase in the formation of hydrogels and cross-linking elements at higher concentration tends to increase the pore space and inhibits the interaction between soil particles leading to a decrease in the dry unit weight at higher concentration (Kwon et al. 2019). In effect, at higher concentrations, the XG treated soils tends to swell due to the higher viscosity of pore fluid and formation of hydrogels and thereby increase the void ratio of the treated soil matrix (Fig. 3b).

OMC increases with the increase in xanthan gum as the biopolymer is hydrophyllic in nature and absorbs more water which is used for the formation of hydrogels (Dehghan et al. 2019). Additional monomers also tend to absorb more water with the increase in the xanthan gum content (Chang et al. 2015). Optimum moisture content also increases substantially at higher concentration due to increased water demand for the formation of hydrogels and cross-linking elements. It increases from 10% for untreated soil to 16% for soil treated with 2% XG, nearly an increase of 37%.

Coefficient of permeability

Table 3 shows the summary of the modification of the permeability coefficient of the treated soil for different periods of curing. The coefficient of permeability decreased with the increase in the biopolymer content. The formation of cross-link elements in the soil matrix filling the pore space obstructs the flow of water. Fig. 3 a (i) and (ii) show the coating on the soil at various biopolymer contents. Also, formation of hydrogels and the increase in the viscosity of pore fluid deters the flow of water through the voids with an increase in the biopolymer content (Dehghan et al. 2019). The decrease in the coefficient of permeability is nearly 1000 times with a small addition of 0.25% xanthan gum to the soil (Table 4). Results of the study showed a marked reduction in the coefficient of permeability as biopolymer content increased. At 5% addition of xanthan gum content, the decrease is approximately 100,000 times. At higher concentration of biopolymer, the more viscous hydrogels fill the pore spaces and clogs the pores. The rate of decrease of the coefficient of permeability with increase in biopolymer content is observed to decrease. Ivanov and Chu (2008), Bouazza et al. (2009), Cabalar et al. (2017) and Dehghan et al. (2019) also report similar observations of decrease in the coefficient of permeability.

Coefficient of permeability of the treated soil is observed to decrease significantly with the increase in the number of days of curing. For example, coefficient of permeability of the soil at 0.25% addition of xanthan gum is 2.82×10^{-6} cm/s immediately after the addition of biopolymer and it decreases to 6.68×10^{-9} cm/s after 90 days. The trend of decreasing coefficient of permeability with the increase in the days of curing indicates that the reactions like formation of hydrogels, cross-linking elements, and pore clogging continue with time (Bouazza et al. 2009). The results show that coefficient of permeability decreases with increase in xanthan gum content and days of curing for all percentages of biopolymer investigated. This also supports the fact that in the soil matrix, the biopolymer has not degraded within the investigated period of 90 days.

Stress strain behaviour and strength

Effect of xanthan gum content on stress-strain behaviour

The soil shows brittle behaviour with a pronounced peak and fails at lower strain (Fig. 4). Addition of xanthan gum causes a significant increase in the resistance of the soil matrix to load. The failure strain increases gradually with the increase xanthan gum content. The viscosity of the xanthan gum increases with the xanthan content (Table 3) and is manifested in stress-strain behavior of the soil. It shows a gradual increase in stress till failure with the addition of xanthan gum. At all percentages of xanthan gum addition, a clear peak is evident, indicating the tendency of xanthan gum to aggregate the soil matrix. At lower xanthan gum contents, there is a gradual reduction in strength but as the xanthan gum content increases, the soils brittle failure with drastic reduction in post-peak strength (Fig. 4).

The formation of cross-link elements and hydrogen bonds (Nugent et al. 2009; Chang et al. 2015, 17, 18) render the soil matrix stiffer, increasing its resistance to load resulting in higher unconfined compressive strength of the soil at all investigated percentages of xanthan gum. Figure 5 shows that the rate of change in stress behavior is clearly distinct at lower concentration but at higher concentration beyond 2%, the stress-strain behavior is almost similar. This indicates that 2% xanthan gum is optimum to increase the strength of the soil.

Table 3 Viscosity of xanthan gum at different concentrations

Xanthan gum (%)	0.25	0.50	0.75	1.00	1.50	2.00	3.00	5.00
Viscosity (cps)	114	355.9	581.9	869.8	1692	2100	4100	Gel

Table 4 Coefficient of permeability of xanthan gum-treated soil

Xanthan gum (%)	Permeability (cm/s) at different days of curing							
	0	1	3	7	14	28	56	90
Soil	10.28×10^{-3}							
0.25	2.82×10^{-6}	4.35×10^{-7}	3.43×10^{-7}	2.11×10^{-7}	9.24×10^{-8}	6.36×10^{-8}	6.50×10^{-8}	6.68×10^{-9}
0.50	2.4×10^{-6}	3.85×10^{-7}	3.14×10^{-7}	1.1×10^{-7}	6.74×10^{-8}	4.13×10^{-8}	3.62×10^{-8}	5.15×10^{-9}
0.75	1.66×10^{-7}	8.22×10^{-8}	4.11×10^{-8}	3.12×10^{-8}	2.68×10^{-8}	2.19×10^{-8}	1.66×10^{-8}	2.99×10^{-9}
1.00	1.63×10^{-7}	7.23×10^{-8}	3.75×10^{-8}	3.07×10^{-8}	2.54×10^{-8}	1.99×10^{-8}	1.48×10^{-8}	1.94×10^{-9}
1.25	1.17×10^{-7}	6.48×10^{-8}	2.02×10^{-8}	2.00×10^{-8}	1.26×10^{-8}	1.00×10^{-8}	8.2×10^{-9}	8.58×10^{-10}
1.50	8.63×10^{-8}	5.29×10^{-8}	1.91×10^{-8}	1.68×10^{-8}	1.37×10^{-8}	7.22×10^{-9}	7.04×10^{-9}	8.21×10^{-10}
1.75	6.45×10^{-8}	3.83×10^{-8}	1.21×10^{-8}	1.08×10^{-8}	1.02×10^{-8}	6.98×10^{-9}	6.57×10^{-9}	7.84×10^{-10}
2.00	5.07×10^{-8}	1.03×10^{-8}	7.61×10^{-9}	7.51×10^{-9}	9.7×10^{-9}	5.87×10^{-9}	3.17×10^{-9}	7.27×10^{-10}
3.00	4.28×10^{-8}	9.62×10^{-9}	7.14×10^{-9}	6.17×10^{-9}	5.64×10^{-9}	4.28×10^{-9}	2.33×10^{-9}	6.92×10^{-10}
5.00	1.29×10^{-8}	6.46×10^{-9}	5.87×10^{-9}	4.77×10^{-9}	2.83×10^{-9}	1.29×10^{-9}	1.07×10^{-9}	6.78×10^{-10}

Also, the results of the experimental investigation show that the peak compressive stress increases along with the failure strain (Fig. 6). The increase in failure strain points to the possibility of large network of interconnected biopolymer soil matrix that resists the loads at higher strains.

Effect of curing on the stress-strain behavior of xanthan gum-treated soil

Figure 6 a and b demonstrate the stress strain behavior of soil at 0.5% and 2% xanthan gum addition for various periods of curing. It can be noted that at lower concentration, the gain of strength with the days of curing is distinct but at higher concentrations, it is though there is a gain in the peak strength, at lower strains, their behavior is similar. Failure strain increases with both the increase in gum content and days of curing (Fig. 6c). The rate of increase is steeper at low concentration of 0.25% but then the rate of increase remains marginal for other xanthan gum contents. Beyond 2% xanthan gum content, there is only marginal increase both the stress and strain with the increase in the days of curing.

Also Fig. 6 points out that maximum strength gain occurs after 7 days of curing and beyond that, the rate of increase in strength decreases. This is true for all the investigated percentages of xanthan gum investigated and for the curing period investigated. Also, a considerable increase in strength and stiffness of the treated soil is observed after longer curing periods (Fig. 6a, b). The strength gain for all percentages of xanthan gum at all periods of curing indicates that the biopolymer has not degraded and continues to strengthen the soil matrix through aggregation, formation of cross-link elements and hydrogen bonds. The micrographs at the various days of curing show these strengthening effects (Fig. 7). Figure 7 a and b show the formation of gel coating on the soil particles. This indicates the possible soil–biopolymer interaction due to the formation of ionic bonds (Dehghan et al. 2020) as result of the anionic nature of xanthan gum. The gel formation in the pores of the soil matrix is observed to increase with curing

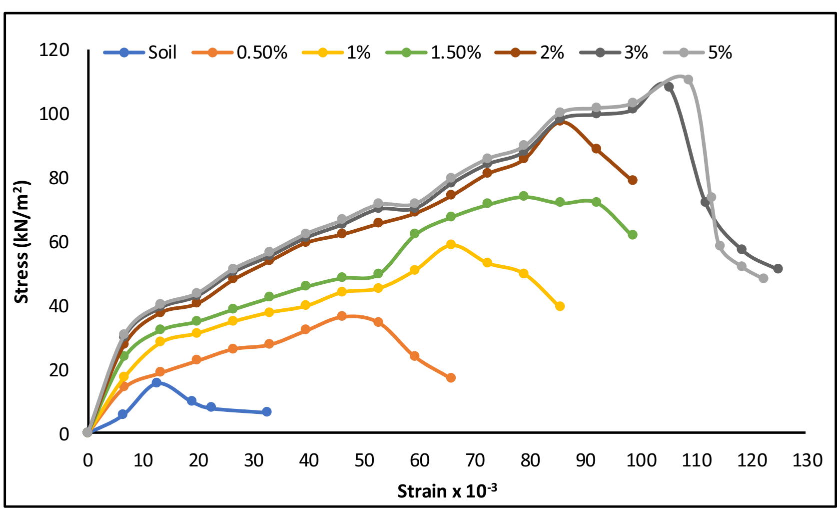

Fig. 4 Stress-strain behavior of Xanthan gum-treated soil immediately after addition of xanthan gum

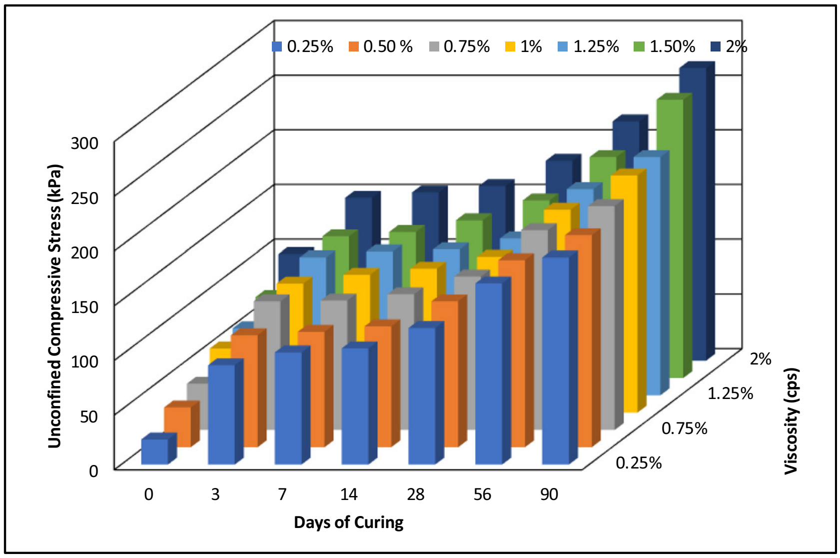

Fig. 5 Viscosity-stress of xanthan gum-treated soils

time as seen in Fig. 7b. The particles are also bound by ionic bonds that impart higher strength and stiffness to the treated soil matrix.

Undrained shear strength and tangential deformation modulus

The results of the study show that the undrained shear strength of the soil increases with the xanthan gum content and with the days of curing. The increase in strength can be attributed to aggregation of the soil particles, formation of an interconnected network of cross-links through cation bridging, and formation of hydrogen bonds (Fig. 7). The pore spaces in the soil matrix are filled with the cross-link elements and hydrogen bond, and the combined action of the xanthan gum and soil matrix renders a stiffer treated soil (Chang et al. 2015; Kwon et al. 2019). There is an increase of 131.84% and 1132.64% in strength at lower concentration of 0.5% after 0 day and 90 days of curing respectively. Similarly, the percentage strength gain is 520.02% and 1601.27% at a higher concentration of 2%

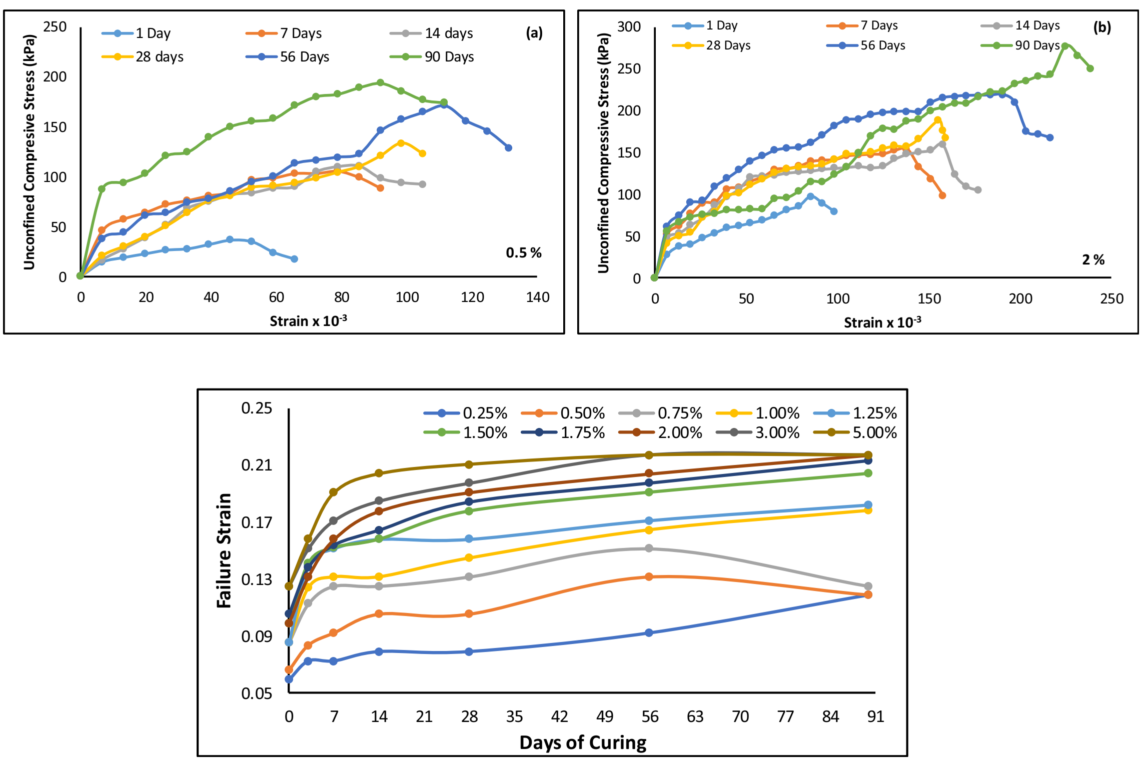

Fig. 6 Stress–strain behavior of xanthan gum-treated soils with curing

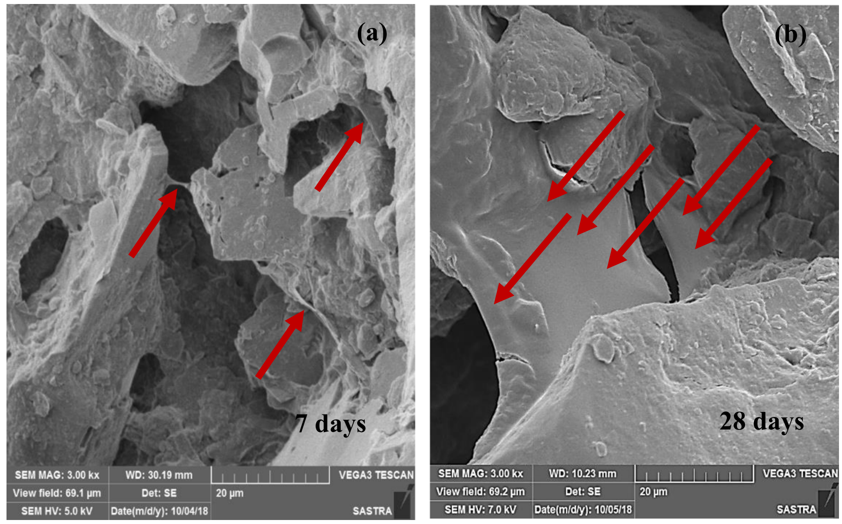

Fig. 7 SEM micrographs of xanthan gum-treated soil at 1.25% for different days

after 0 day and 90 days of curing. The rate of increase in strength with the increase in xanthan gum and days of curing can be expressed as follows:

$$\text{Undrained shear strength} = 80.56 + 1.595 \times (\text{days of curing}) + 15.451 \times (\%\text{xanthan gum content}) \quad (3)$$

Equation 3 shows that both days of curing and xanthan gum content positively affect the strength of the treated soil. Also gum content is observed to be the dominant controlling in enhancing the strength than the days of curing. The modulus of deformation (tangential modulus) of the soil also shows an increase with the increase in xanthan gum content and curing period. The soil matrix is rendered stiff with the addition of xanthan gum, and hence, at higher strain rates, the deformation modulus increases (Fig. 8).

Conclusions

The study investigated the choice of using xanthan gum a polysaccharide for improving the geotechnical properties of the soil. The following conclusions were drawn from this study.

(i) Index properties and classification

Biopolymer treatment increased the plastic nature of the soil. The consistency limits—liquid, plastic, and shrinkage limit increased with the increase in biopolymer content. The plasticity index of the soil also increased and as a result at higher concentrations of xanthan gum, the soil was reclassified as highly compressible clay from low compressible clay.

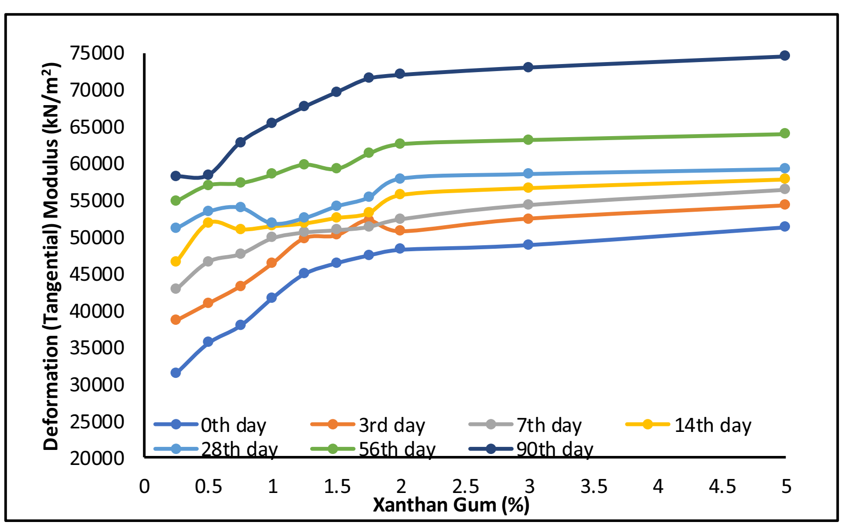

Fig. 8 Deformation (tangential) modulus of xanthan gum-treated soil

(ii) Compaction characteristics

At low concentration, an increase in dry unit weight was observed due to the tendency of the biopolymer to induce aggregation of soil particles but with increase in xanthan gum content, the viscosity of the pore fluid increased and this caused an increase in void ratio leading to a decrease in the maximum dry density. The optimum moisture content also showed an increase with the xanthan gum content.

(iii) Permeability

The addition of biopolymer reduced the permeability of the soil tremendously. A reduction of nearly 100,000 times was observed at higher concentrations of xanthan gum. The decrease in permeability increased with the days of curing.

(iv) Strength

The treated soil matrix was rendered stiffer due to the formation of cross-link elements and hydrogen bonds. The unconfined compressive strength of the soil increased by 131.84% at 0.5% addition of xanthan gum after 0 day of curing and 1132.16% after 90 days of curing. Similarly, at 2% addition, an increase in strength of 520.02% was observed after 0 day of curing and 1601.27% after 90 days of curing. The strength of the treated soil increased with days of curing.

The above conclusions indicate that the xanthan gum can be used for various geotechnical applications: (i) hydraulic barrier or seepage barrier, (ii) contaminant barrier, (iii) improve bearing capacity of the soil, (iv) subgrade improvement and (v) slope stabilization.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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