Effects Of Fines Content On The Strength And Stiffness Of Biopolymer Treated Low-Plasticity Soils

Article *in* Australian Geomechanics Journal · March 2023

DOI: 10.56295/AGJ5811

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This is a final draft. Full citation is below:
Gedela, R., Indraratna, B., Medawela, S., and Nguyen, T.T. 2023. Effects of fines content on the strength and stiffness of biopolymer treated low-plasticity soils. Australian Geomechanics Journal 58(1): 33-41. doi: https://doi.org/10.56295/AGJ5811.

EFFECTS OF FINES CONTENT ON THE STRENGTH AND STIFFNESS OF BIOPOLYMER TREATED LOW-PLASTICITY SOILS

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ABSTRACT

The use of biopolymers to enhance the engineering properties of soil has received increasing attention in recent years, however, the interactive role that biopolymers and the fines content of the soil play in governing the geotechnical parameters still requires insightful investigation, in relation to chemical soil treatment that can be ecologically detrimental. This paper examines the combined effects of Xanthan Gum (XG) derived from specific bacterial strains and the presence of clay fines content (kaolin) on the strength and stiffness of low plasticity soils, with special reference of cyclic traffic (road and rail) loading. In this study, fine sand is mixed with different contents of kaolin, whereby laboratory compression and tensile tests were conducted on natural (untreated) and XG-treated soil specimens. The results indicate that soil strength can be enhanced significantly when XG is added, however the effectiveness is a function of the kaolin content (KC). At an optimum XG content of 2% and a fines content increasing from 5% to 30%, split tensile strength increases from 230 to 750 kPa, while the unconfined compressive strength rises from 1.4 to 7.9 MPa, respectively. For XG content between 0.5% and 2%, the small strain stiffness of treated soil increases fourfold from 206 to 854 MPa.

Keywords: Xanthan gum, fines content, ground improvement, UCS, small strain stiffness, tensile strength,

1 INTRODUCTION

It is often observed that subgrades with low plasticity and certain embankment fill materials can succumb to bearing capacity failure or become vulnerable to mud pumping under repeated cyclic loads due to a lack of cohesive strength (Duong et al. 2014; Chawla and Shahu 2016; Indraratna et al. 2020). In this mode of failure, soil particles with low cohesive bonding tend to migrate upwards when they are subjected to cyclic loading, resulting in severe loss in shear resistance of the foundation (Nguyen et al. 2020). Hence, improving such soils with suitable and sustainable ground improvement methods is essential to safely support and withstand heavy and continuous traffic loads on roads and railways. Conventional ground improvement methods such as lime stabilization and grouting impose environmental threats owing to quarrying substantial volumes of raw materials, thus adversely affecting land use, and increasing the groundwater pH (De Jong et al. 2010). Soil stabilization using naturally occurring materials such as biopolymers has therefore gained greater attention in recent years.

Various biopolymeric materials such as Agar Gum, Gaur gum, Gellen Gum Dextran, Beta-(1-3)-glucan and Xanthan Gum have been used to enhance the engineering properties of soils in recent years (Khatami et al. 2013; Tran et al. 2014; Chang et al. 2015; Lin et al. 2016; Smitha et al. 2016; Hataf et al. 2018; Lee et al. 2017 & 2019; Chen et al. 2020; Jiang et al. 2022). Xanthan Gum (XG) was selected as the preferred biopolymer for soil treatment in the current study, due to the cost effectiveness stable at wide range of pH (2 to 12) compared to the other biopolymers. The effects of XG on the geotechnical properties of natural soils have been addressed in previous studies (Chang et al. 2015; Cablar et al. 2018; Lee et al. 2017 & 2019), while some other studies (Bouazza et al. 2009, Biju and Arnepalli 2020) have investigated hydraulic characteristics of silty sand and bentonite-sand mixtures. Nguyen et al. (2021) demonstrated how kaolin fines content can be altered to mitigate subgrade soil fluidization under railway loads. However, none of the past studies have highlighted the simultaneous influence that clay fines and XG contents can have on the basic compressive and tensile strengths and stiffness (secant and small strain shear modulus). The mechanism that XG interacts and stabilises the soil matrix significantly with coarse and fine particles (Latifi et al, 2017, Cabalar et al. 2017) is not obvious and needs further elaboration through basic testing.

In view of the above, this study presents the results of a series of laboratory tests, based on unconfined compressive tests, split cylinder tensile strength tests and Bender elements for small strain stiffness. These results will contribute to a greater understanding of the use of XG to remediate problematic subgrade soils such as low-plasticity soils, which are vulnerable to fluidization upon cyclic traffic loading.

2 MATERIALS

Fine kaolin clay, medium-coarse sand and Xanthan Gum (XG) were used to prepare specimens for testing. Basic material properties such as the particle size distribution, specific gravity (G), Plasticity Index, (PI) and the compaction characteristics (maximum dry density (γ_d) and optimum moisture content (OMC)) of clay-sand mixtures (CSMs) are shown in Table 1 and Figure 1. In case of CSM_5 and CSM_{10} (subscripts 5 and 10 denote the percentage of kaolin fines content), *PI* cannot be determined as they contain less fines contents, thus negligible. On the other hand, *PI* of CSM_{20} and CSM_{30} are 6.2 and 9.3 (Figure 1b), respectively, and these two soils are classified as low plastic soils (*PI*< 20). Xanthan Gum (XG) produced by the *Xanthomonas campestris* bacterium (Katzbauer 1998) was used in the current study.

Table 1: Basic material properties of various clay sand mixtures (CSMs)

Soil	Fines content (%)	OMC (%)	$\gamma_{d, max}$ (kN/m^3)	Liquid Limit, LL, (%)	Plastic limit, PL (%)	Plasticity Index, PI (%)
CSM_5	5	8.26	16.74	15.3	_	Non-Plastic
CSM_{10}	10	8.83	17.69	17.1	_	Non-Plastic
CSM_{20}	20	9.91	19.20	18.6	12.4	6.2 (low plastic)
CSM_{30}	30	10.54	18.84	23.4	14.1	9.3 (low plastic)

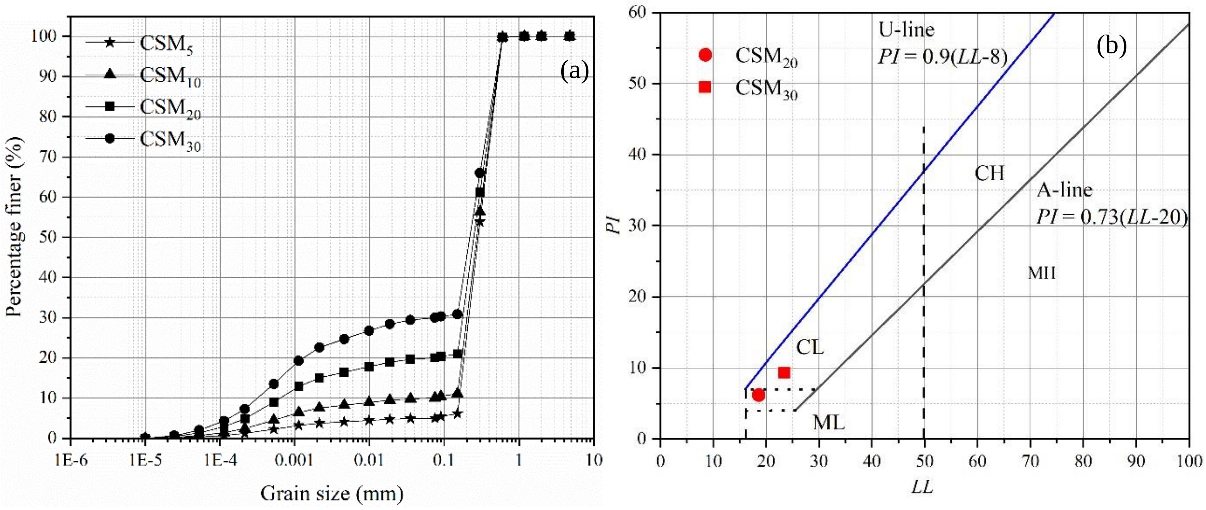

Figure 1: (a) grain size distribution cure and (b) plasticity of the tested soil

3 METHODOLOGY

3.1 SPECIMEN PREPARATION

Kaolin clay was mixed with sand at different contents, i.e., KC = 5%, 10%, 20% and 30% to create low-plasticity soil specimens (i.e., clay-sand mixture CSM), while different Xanthan Gum (XG) contents 0.5%, 1%, 1.5%, 2%, 3%, and 4% were considered for soil treatment. The dry mixtures were then mixed with water at the optimum moisture content (OMC) and stored in an airtight cover for two hours to achieve uniform distribution of moisture. The soil was then compacted in 10 layers in a cylindrical mould (50 mm diameter and 100 mm height), and the sample was extruded from the mould for testing. Those specimens with 5% and 10% fines (i.e., CSM_5 and CSM_{10}) became disintegrated while being extruded, whereas for higher contents of fines (i.e., CSM_{20} and CSM_{30}), the specimens could retain their shape after extrusion because of larger cohesive strength induced by Kaolin fines. A similar process was applied to the biopolymer treated soil specimens, which were prepared in accordance with the procedure outlined by Latifi et al. (2017). Unlike the untreated soils, the XG treated soil specimens for different fines contents retained their shape regardless of fines and XG contents. The extruded specimens were cured at a controlled room temperature of 25°C for 28 days.

3.2 TEST DETAILS

A series of unconfined compressive strength (UCS) tests were carried out on the prepared specimens in accordance with ASTM D2166 (2016) to assess the strength characteristics under uniaxial compressive loading. The UCS is a standard measure used by most transportation agencies to classify stabilized materials, mainly because it is simple to conduct as a basic index test (Vorobieff 2004). In this study, the UCS for each data point was calculated by considering the average of three trials carried out for each mixture.

The Brazilian tensile test is one of the most common tests used to determine the tensile strength of stabilized soils, albeit it was only developed for brittle materials. Tschebotarioff (1973) stated that soils are classified as brittle if the percentage of strain at failure is < 8% in a standard UCS test. In this current study, the percentage strain at failure varied from 1% to 3% (the detailed results shown later in this paper). Therefore, the stabilized dehydrated samples could be considered brittle. A set of Brazilian tests were carried out on 50 mm diameter by 100 mm high samples, as per ASTM D3967 (2008), to assess the tensile strength of treated and untreated soil specimens (Eq. 1).

$$\sigma_t = \frac{2P}{\pi DH} \quad (1)$$

where σ_t is the split tensile strength, P is the load at failure, D is the diameter, and H is the height of the specimen.

A series of Bender element tests was also performed to measure the shear wave velocities and small strain shear modulus of soils treated with XG, where the amount of XG varied from 0.5% to the optimum biopolymer content (OBC). The shear modulus under small strain loading was then calculated by:

$$G_{max} = \rho \ V_s^2 \quad (2)$$

where V_s is the shear wave velocity, G_{max} is the small strain shear modulus, and ρ is the density of soil.

4 RESULTS AND DISCUSSION

4.1 INFLUENCE OF XG AND FINES CONTENTS ON SOIL STRENGTH

The UCS of untreated soils with 20% (CSM_{20}) and 30% (CSM_{30}) fines content was found as 0.083 MPa and 0.118 MPa, respectively (Figure 2a), whereas the same soils treated with 0.5% of XG reached 1.83 MPa and 2.60 MPa. This means when XG content was 0.5% in $CSM_{20,}$ the UCS of the treated samples was approximately 22 times higher than the untreated samples. Comparatively, the strength of the CSM_{30} treated with 0.5% XG was 55 times higher than the untreated sample, implying that fines content can significantly affect the efficiency of using XG to improve strength of soils. These results also infer that even a minor percentage of XG (e.g., 0.5%) can significantly improve the strength of low plastic soils (PI < 20). In case of pure sand (without kaolin), the XG biopolymer in contact with the surfaces of sand particles forms a strong film and interparticle bridges between individual sand particles (Figure 3). On the other hand, for clay-sand mixtures, apart from the coating (i.e., XG film) around sand particles, the XG anionic biopolymer directly interacts with surface charges (cations) of clay particles, to form additional bonds through electrostatic interactions (Latifi 2017).

The UCS of treated CSMs also increased with the increasing XG content. For instance, the UCS of CSM_{30} treated with 0.5% was 2.6 MPa, whereas the UCS of CSM_{30} with 4% of XG was 9.8 MPa, an increment of almost 4 times. However, the UCS of all the CSMs increased significantly until the XG content increased up to 2%, after which the increment in UCS was marginal (Figure 2a). Hence, a XG content within the range of 1.5 - 2% would be the optimum biopolymer content (OBC). The combined effect of clay fines and XG (up to an OBC of 2%) on UCS is shown in the three-dimensional plot (Figure 2b). The highest UCS was 7.92 MPa at 2% XG (i.e., OBC) and 30% fines content (CSM_{30}), while the lowest value was 300 kPa at 0.5% XG and 5% fines content (CSM_5). These results infer that the efficiency of using XG to improve the UCS of soil becomes more significant when the soil has more fines (Figure 2a & b). Figure 3 shows that when a coarse grain matrix is combined with fine cohesive particles and an hydrated biopolymer such as XG, there are many bonds formed with enhanced electrostatic attraction and increased contact surface area within the soil matrix. The measured values of UCS in the current study are in the common range of UCS reported in past studies using XG to treat silty sand for transport infrastructure (e.g., Lee et al. 2019). Figure 2(c) shows how the current UCS values of treated test specimens with 2% XG are compared to the required soil strength suggested by several design codes for the sub-base (Austroads 2019; IRC 2012 ; MOLIT 2012) . The evaluation shows that the achieved UCS of treated soils with 5-30% fines contents can satisfy the required UCS > 1 MPa according to Austroads 2019, whereas without XG, the soil fails to meet the requirement.

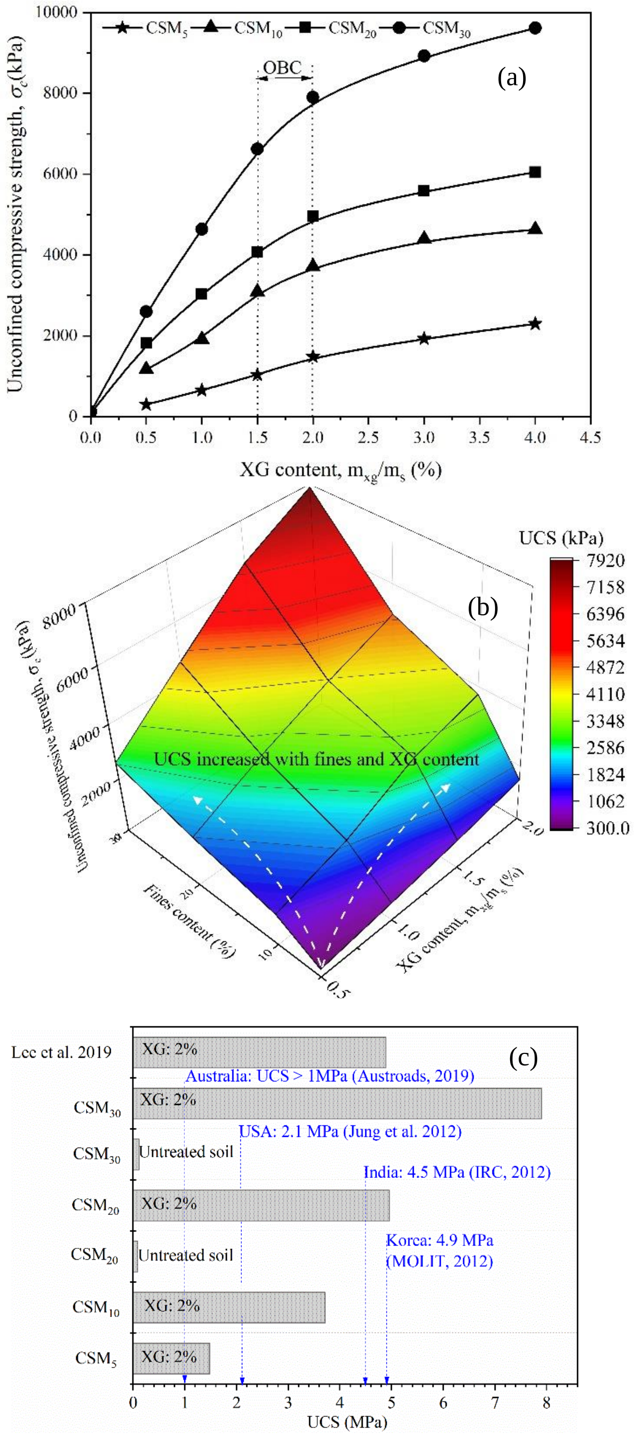

Figure 2: (a) Influence of XG content on the UCS; (b) variation of UCS with both fines and XG contents; (c) the UCS values of soil treated with 2% XG at different fines contents compared to the strength required for road (subbase)

The split tensile strength of all the CSMs increased significantly until the percentage of XG reached 2% (Figure 4a), and beyond this threshold, the improvement was negligible. For example, for CSM_{20}, the split tensile strength increased from 190 kPa to 580 kPa as the percentage of XG varied from 0.5 to 2%, but when the percentage of XG increased from 2 to 4%, the change was only from 580 kPa to 650 kPa. At an optimum biopolymer content of 2%, the split tensile strength increased significantly from 230 kPa to 750 kPa when fines content rose from 5% to 30%. It is evident that a relevant combination of Xanthan Gum and kaolin fines contents is an efficient and eco-friendly approach to enhance the tensile strength of low plastic soils. As a result, the subgrade soil can effectively sustain under tensile stresses developed at the subgrade and base/capping layers under repeated loads. The relationship between the UCS (σ_c) and split tensile strength

(σ_t) of XG treated soils is shown in Figure 4(b). With the $R^2 > 0.95$, the results indicate that the split tensile strength (σ_t) of CSMs can be estimated as approximately 0.12 times that of UCS (σ_c) (Eq. 3).

$$\sigma_t = 0.12\sigma_c \quad (3)$$

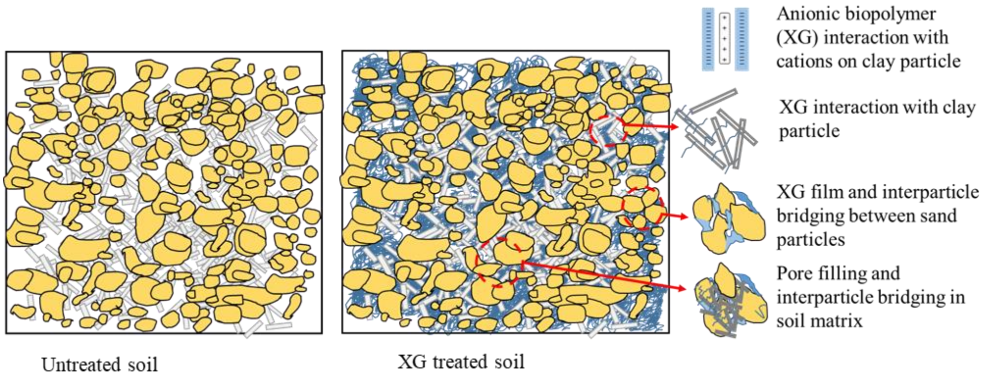

Figure 3: Mechanism of XG biopolymer interaction with fines and sand particles in soil matrix

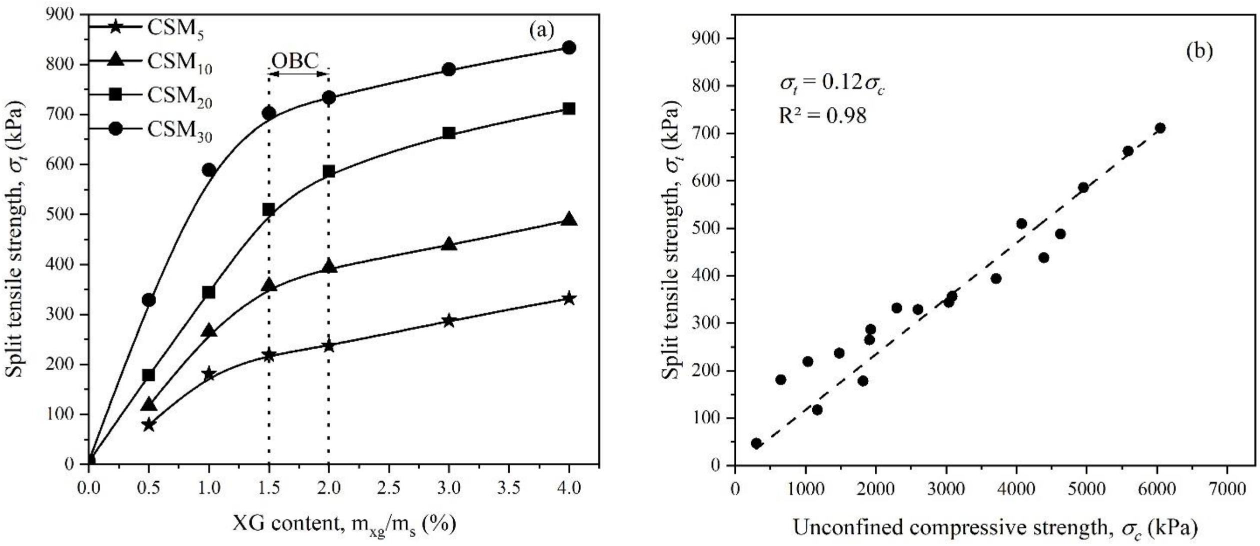

Figure 4: (a) Influence of XG content on the tensile strength; (b) relationship between the tensile strength and unconfined compressive strength (UCS)

4.2 SECANT MODULUS

The stress-strain behaviour of XG-treated CSMs (Figure 5a to 5d)) under uniaxial compression has shown a stiffer response as the XG content increased. The effect of fines and XG contents on the stiffness of the various CSMs considered in this current study is further demonstrated by assessing the secant modulus, E_{50} (i.e., the slope of the line passing through the origin and the point at 50% of peak stress). The secant modulus (E_{50}) of untreated soils with 20% and 30% of fines (CSM_{20} and CSM_{30}) was calculated as 4.43 MPa and 8.53 MPa, respectively, whereas the E_{50} of the same CSMs treated with 0.5% XG is 103 MPa and 167 MPa, respectively. These results indicate that a small amount of XG could considerably enhance E_{50} of the soil (Figure 6a). Likewise, the presence of fines in the treated soils significantly influenced its stiffness. For example, for the same amount of XG, i.e., 0.5%, the E_{50} increased from 37 to 167 MPa when the fines content was increased from 5 to 30%.

4.3 STRAIN ENERGY DENSITY

The strain energy density of a material is defined as the strain energy per unit volume and can be represented by the fundamental definition:

$$U = \int_0^{\varepsilon} \sigma . d\varepsilon \quad (4)$$

The above describes the amount of work done to deform soil under uniaxial compression or via a tension test. The current study computed the strain energy density based on UCS test results, i.e., the area under the stress-strain response with the strain varying from zero to the value corresponding to the peak stress. The influence of XG and fines on the strain energy density is shown in Figure 6(b). When the percentage of XG increased, the strain energy density also increased until the OBC (2%), beyond which there was a negligible increment in strain energy in all CSMs. This response could be attributed to an insignificant increment in peak strength (Figure 5). Figure 6(b) shows that as the XG and fines contents increase, the amount of work needed for the sample to fail also increases. For example, the strain energy stored in the sample increased substantially from 1.85 kJ/m^3 to 100.98 kJ/m^3 when XG contents increased from 0.5% to 2% (OBC) and fines content increased 5% to 30%. This proved that simultaneously controlling fines and XG contents can promote the energy required to cause soil to deform, thus enhancing the soil strength and stiffness.

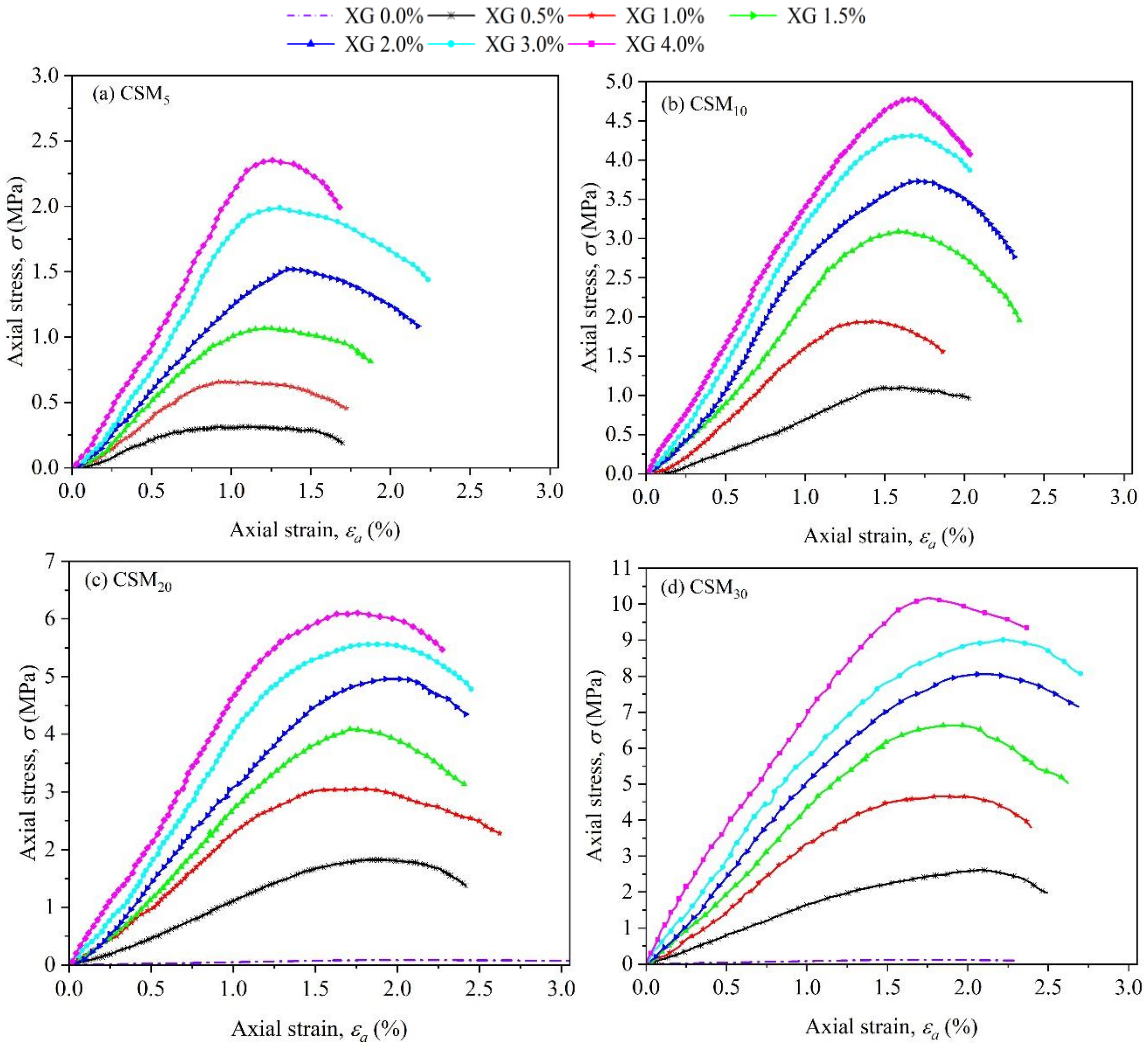

Figure 5: Stress-strain response of various XG-treated soils

4.4 SMALL STRAIN STIFFNESS

Shear wave velocity of XG-treated soils was measured using Bender elements. The shear wave mainly propagates through the solid skeleton (i.e., through particle contact) in the soil matrix, and it is increased with the density of the specimen (Nguyen et al. 2021). Figure 6(c) shows that the shear wave velocity of soils increased with rising XG and fines contents. For instance, when XG content increases from 0.5% to 2%, the shear wave velocity of CSM_{30} varied from 550 m/s to 665 m/s, and the corresponding small strain shear modulus (G_{max}) varied from 571 MPa to 853 MPa. Interestingly, the shear wave velocity and G_{max} of CSM_{30} for all XG percentages were higher than the CSM_{20} despite less unit weight (Figure 6c). This behaviour can be attributed to the apparent cohesion between XG and fines, as discussed earlier in section 4.1. The lowest G_{max} of soils treated with XG is 207 MPa for soil with 5% fines (CSM_5) and 0.5% XG contents, whereas the highest value is 852 MPa for soil with 30% fines (CSM_{30}) and 2% XG. As the contents of fines and XG increased, the generated pulse via Bender elements travelled faster through the more solid and greater contact network formed by finer particles and biopolymer bridges (Figure 7). This attests to the larger strength and stiffness that the soil can obtain when increasing fines and XG contents detailed earlier. The improvements in strength and stiffness of XG treated CSMs with an optimum 2% of XG are listed in Table 2.

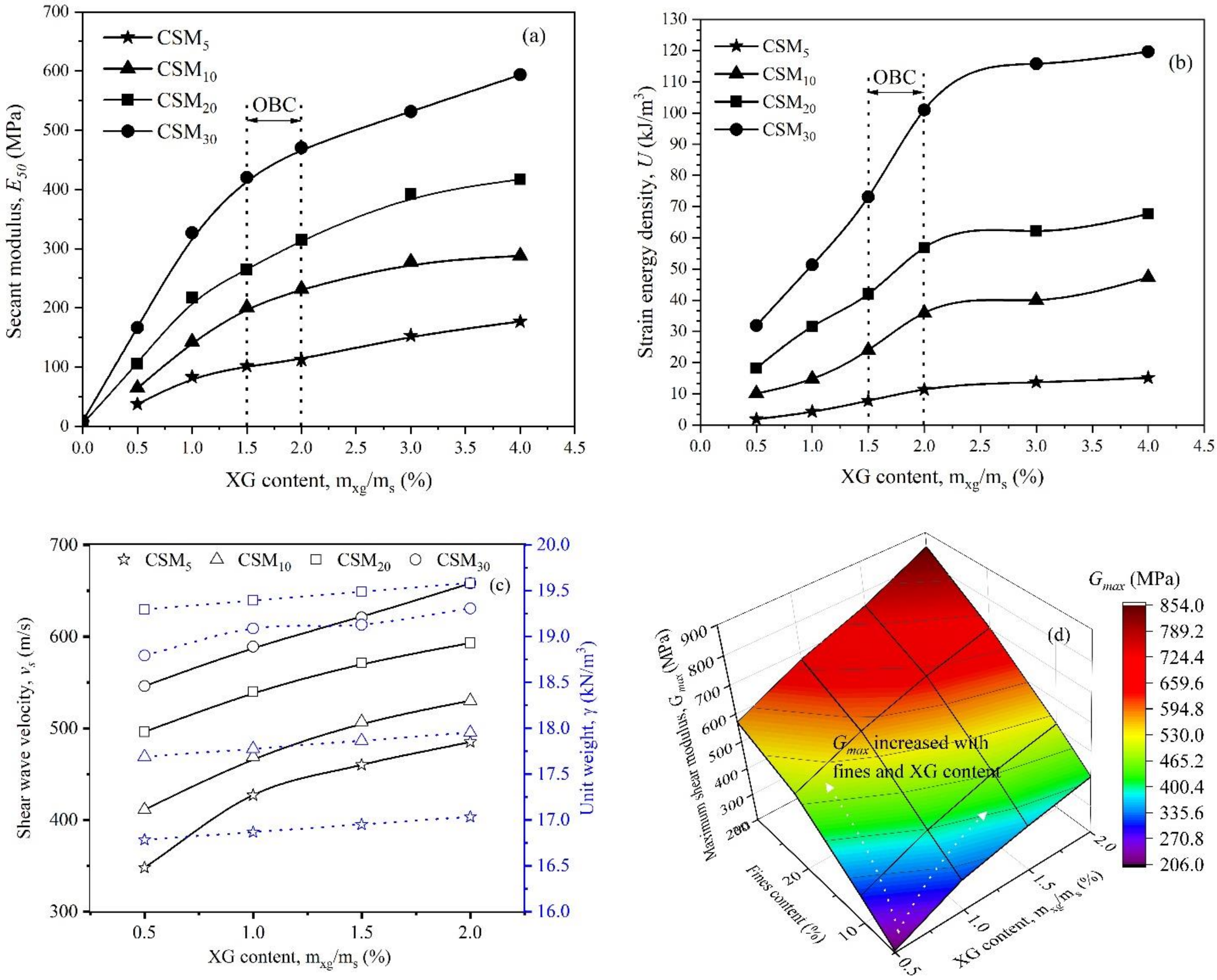

Figure 6: Coupled effect of XG and fines contents on; (a) secant modulus, E_{50} (b) strain energy density, U (c) shear wave velocity, V_s (d) small strain shear modulus (G_{max})

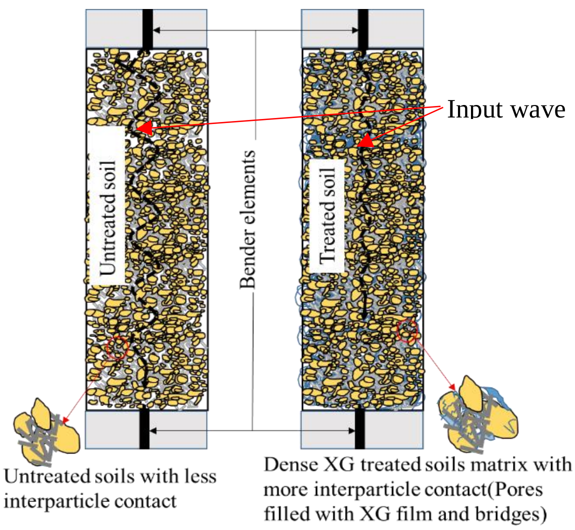

Figure 7: Bender element testing on specimen and propagation of input wave

Table 2: Strength and stiffness characteristics of soils treated with 2% optimum XG content

Soil	UCS, σ_c (MPa)	Split tensile strength, σ_t (MPa)	Secant modulus, E_{50} (MPa)	Strain energy density, U (kJ/m^3)	Small strain shear modulus, G_{max} (MPa)
CSM_5	1.483	0.237	112	11.35	408
CSM_{10}	3.712	0.397	232	35.90	514
CSM_{20}	4.955	0.586	315	56.80	702
CSM_{30}	7.904	0.736	470	100.98	852

5 CONCLUSIONS

The current study investigated the effectivenss of adding the biopolymer Xanthan Gum (XG) to improve the strength and stiffness properties of a low-plasticity soils considering the role of its fines conten (kaolin). The results showed that increasing XG contents up to the optimum ratio of 1.5-2% can significantly enhance the unconfined compressive strength, uniaxial (split cylinder) tensile strength, deformation or secant modulus and the small strain stiffness of the soil. The unconfined compressive strength (UCS) of the CSM_{20} specimen increased considerably by a factor of 22 when only a small amount of XG (0.5%) was added. However, this effectiveness can be further enhanced by increasing the fine clay (kaolin) content in the treated soil . For the same XG content (e.g., 2%), the UCS was found to be more than 5 times greater when the kaolin fines content increased from 5% to 30%. Similarly, the tensile strength increased more than 3 times. The secant deformation modulus and the small strain stiffness (G_{max}) increased by a factor of 12.7 and 4.1, respectively. The study proved that the use of biopolymer (Xanthan Gum) can significantly enhance the basic strength-deformation properties of low-plasticity soils by optimizing the clay fines content in the treated soils.

6 ACKNOWLEDGEMENTS

This research was financially supported by a UTS International Research Scholarship and the Transport Research Centre (TRC), University of Technology Sydney. This support is gratefully acknowledged.

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