Performance evaluation of β-glucan treated lean clay and efficacy of its choice as a sustainable alternative for ground improvement

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Abstract. The choice of eco-friendly materials for ground improvement is a necessary way forward for sustainable development. Adapting naturally available biopolymers will render the process of soil stabilization carbon neutral. An attempt has been made to use β-glucan, a natural biopolymer for the stabilization of lean clay as a sustainable alternative with specific emphasis on comprehending the effect of confining stresses on lean clay through triaxial compression tests. A sequence of laboratory experiments was performed to examine the various physical and mechanical characteristics of β-glucan treated soil (BGTS). Micro-analysis through micrographs were used to understand the strengthening mechanism. Results of the study show that the deviatoric stress of 2% BGTS is 12 times higher than untreated soil (UTS). The micrographs from Scanning Electron Microscopy (SEM) and the results of the Nitrogen-based Brunauer Emmett Teller (N_2-BET) analysis confirm the formation of new cementitious fibres and hydrogels within the soil matrix that tends to weld soil particles and reduce the pore spaces leading to an increase in strength. Hydraulic conductivity (HC) and compressibility reduced significantly with the biopolymer content and curing period. Results emphases that β-glucan is an efficient and sustainable alternative to the traditional stabilizers like cement, lime or bitumen.

Keywords: biopolymer; β-glucan; shear strength; hydraulic conductivity; compressibility

1. Introduction

The use of traditional soil additives like lime, cement and bitumen, etc., lead to a host of environmental issues (Chang and Cho 2012, Blanck *et al.* 2013, Chang *et al.* 2016a, Chang *et al.* 2019). Chief among them is the fact that they modify the soil environment permanently. These additives change the pH of the soil, deter plant growth and pollute both soil and ground (Chang *et al.* 2015a, 2016a, Fatehi *et al.* 2018, Chang *et al.* 2019). Also, in their production stage, additives like cement release greenhouse gases like carbondioxide and nitrogen oxides leading to global warming (Fatehi *et al.* 2018, Chang *et al.* 2019) and in addition their use results in a number of health hazards. These environmental concerns mandate the need for environmental friendly and sustainable additives to modify the geotechnical properties of the soil favourably (Chang *et al.* 2015b, Chang *et al.* 2019, Latifi *et al.* 2016a, Dehghan *et al.* 2018). The choice of a soil stabilizer is dictated by its cost, availability and long-term performance. Hence, any new material for use as soil stabilizer needs thorough investigation. Various material like inorganic ashes from agriculture and industrial waste, geopolymers, biological stabilizers, etc., were investigated by several researchers (Blanck *et al.* 2013, Ayeldeen and Negm 2014, Swain 2015, Chang *et al.* 2019) as alternatives to conventional stabilizers like cement. Bio-cementation technique was also used to augument the geotechnical properties of soil (Sidik *et al.* 2014).

Biological methods are emerging as an attractive alternative to modify the geotechnical properties of soil (Sari 2014, Chang *et al.* 2016b, Ayeldeen *et al.* 2017) and has shown much potential for intense research though their application in the field is limited to-date. Few authors have experimented with the option of using biopolymers for geomaterial stabilization (Chen *et al.* 2013, Maghchiche *et al.* 2013, Chang *et al.* 2016a, Latifi *et al.* 2016b, Dehghan *et al.* 2018, Fatehi *et al.* 2018, Gopika and Mohandas 2019). They are the most popular biological additives used to modify the soil properties. They form highly viscous suspensions with water and are stable over an extensive range of temperature and pH (Vossoughi and Buller 1991, Bouazza *et al.* 2009, Ayeldeen *et al.* 2017). They show favourable properties like pseudo-plasticity, gelling tendency and resistance to shear degradation that enable pore plugging (Wiszniewski and Cabalar 2014). Biopolymers like xanthan gum, guar gum, gellan gum, chitosan have shown appreciable modification in the strength, permeability, compressibility and dynamic stability of the treated soil (Khachatoorian *et al.* 2003, Latifi *et al.* 2015, 2016c, Im *et al.* 2017, Chang and Cho 2018, Dehghan *et al.* 2018, Fatehi *et al.* 2018, Anandha Kumar and Sujatha 2019). They fill the void spaces in granular soil effectively (Liu *et al.* 2018), thus boost the strength and reduce the permeability of the treated soil (Bouazza *et al.*

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2009, Chang and Cho 2014, Chang *et al.* 2016b, Ayeldeen *et al.* 2017, Dehghan *et al.* 2018, Liu *et al.* 2018). A study on xanthan gum and starch treated soil show that it promotes vegetative growth (Tran *et al.* 2019).

A small quantity of biopolymer is sufficient to modify the properties of the soil and hence, the choice of biopolymers can also be an economic option (Ayeldeen *et al.* 2017). They find immense application in erosion control, stabilization of aggregates, as temporary hydraulic barriers and in mud-drilling operations, etc., (Chang and Cho 2014).

Inadequate knowledge of material behaviour (i.e., the treated soil, non-standardization of laboratory testing procedures and field evaluation performance) are the key factors that limit their use in the field (Ivanov and Chu 2008). The mechanism of improvement of geotechnical properties depends on several factors like the type of biopolymer, method of mixing of the biopolymer, days of curing and nature of soil (Bouazza *et al.* 2009, Chang and Cho 2014, Chang *et al.* 2016, Ayeldeen *et al.* 2017, Liu *et al.* 2018).

β-glucan is a widely found polysaccharide derived from the cell wall of cereals, barley, yeast, oat, wheat, bacteria and fungi (Wang *et al.* 2017) and has several applications in the field of medicine. The choice of β-glucan results in a clean soil environment does not pollute groundwater and is also energy efficient (Zhu *et al.* 2016). In the field of civil engineering, it finds application as a super-plasticizer in concrete as it helps in improving the fluidity of cement slurry (Nara *et al.* 1994) and makes concrete more workable. It was first used by Chang and Cho (2012, 2014) as an additive to enhance the various geotechnical properties. Very limited research is available on β-glucan and is limited to inorganic silt type of soil (Chang and Cho 2012, 2014). Chang and Cho (2012, 2014) reported the effect of β-glucan on the strength parameters using uniaxial compression strength. However, the effect of β-glucan on the strength parameters for various shear conditions using triaxial tests is necessary to understand their behaviour under in-situ conditions. Similar study was done by using xanthan gum biopolymer to investigate the stregthening effects of biopolymer treated soil for various confining pressures (Lee *et al.* 2019).

Though few authors (Chang and Cho 2014, Anandha Kumar and Sujatha 2019) studied the hydraulic conductivity of the BGTS, there was no study on the effect of β-glucan treatment on hydraulic conductivity with time. Further studies particularly on the mechanism to understand strength gain and the bio-plugging process will expedite the technology for the choice of β-glucan for soil stabilization in the field. This study addresses the research gap on the studying effect of β-glucan treatment on lean clay with time.

An attempt has been made to study the effect of β-glucan on improving the geotechnical properties of lean clay, particularly its strength, permeability and compressibility for various shear conditions, and curing periods. The strength enhancement mechanism is also discussed in detail with the help of microstructural studies.

2. Materials

2.1 Soil

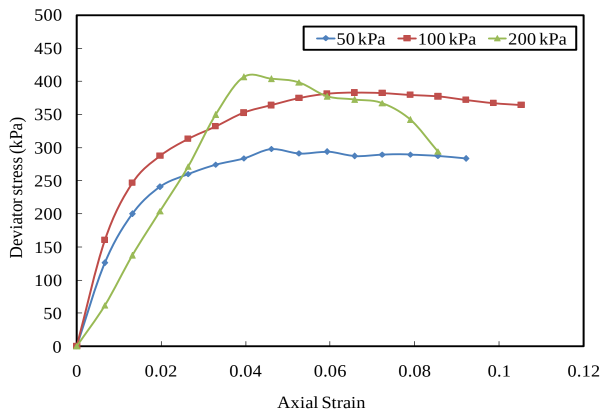
The soil was extracted 1.5 m below the ground from trenches excavated for sampling. The organic content in the soil is less than 2%. X-Ray Diffraction (XRD) analysis of the soil indicates that it contains clay minerals kaolinite, dickite, imogolite, allophane, palygorskite, pargasite and sepiolite. The index and engineering properties of the soil are shown in Table 1. The soil is fairly permeable with moderate plastic behaviour.

The soil falls in the lean clay category based on the Unified Soil Classification (UCS) system.

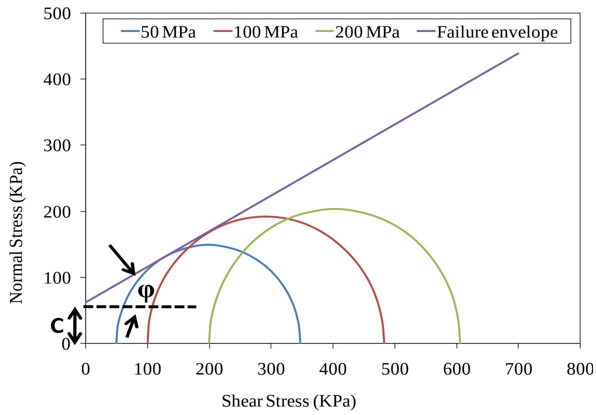
Fig. 1 depicts the stress-strain behavior of the UTS and its corresponding Mohr-Coulomb failure envelope.

Table 1 Geotechnical Properties of UTS

Properties	Value
Specific Gravity	2.28
Liquid Limit (%)	38.3
Plastic Limit (%)	19.1
Shrinkage Limit (%)	14.8
Plasticity Index (%)	19.2
Flow Index	22.9
Swell Index (%)	4.30
Permeability (cm/s)	10.28×10^{-3}



(a) Stress-strain behaviour of UTS



(b) Mohr-Coulomb failure envelope for UTS

Fig. 1 Strength characteristics of UTS

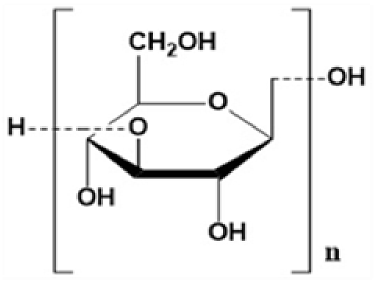


Fig. 2 Molecular Structure of the β-1,3 Glucan Derived from Yeast (Volman *et al.* 2008)

Deviatoric stress is observed to increase from 297.63 kPa to 406.33 kPa when the confining pressure increased from 50 kPa to 200 kPa. The cohesion and angle of internal friction of lean clay selected for the study are 62 kPa and 28.37° respectively.

2.2 β-glucan

β-glucan is brown in colour and is usually derived from different sources like the cell wall of bacteria, yeast and fungi like mushrooms and also is present in plant cellulose. Generally, it has a molecular weight ranging from 0.04 kDa to 1000 kDa (Zhu *et al.* 2016). β-glucan used for this study was purchased from the Meteoric Biopharmaceuticals, Ahmedabad, India. The source of the biopolymer used for the study is Saccharomyces cerevisiae, a species of yeast. Generally, yeast-derived β-1,3/1,6 glucan is supposed to have greater biological activity (Rahar *et al.* 2011). Fig. 2 shows the molecular structure of the β-glucan used for this study. It contains a β-1,3 carbon backbone with elongated β-1,6 carbon branches. It has a tendency to absorb water through hydrogen bonding and also plugs the pores through swelling (Chang *et al.* 2014). On dehydration, it increases the interparticle interaction of the biopolymer in the soil matrix (Chang *et al.* 2014).

3. Experimental investigation

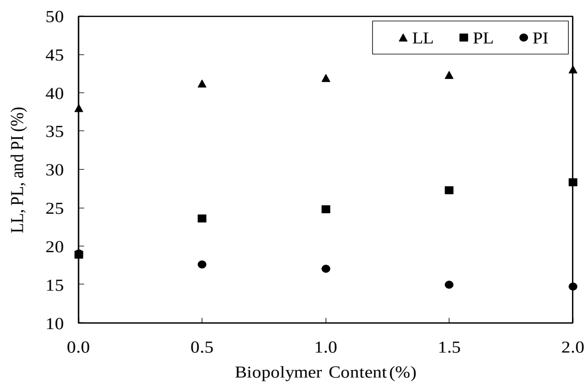
The treated soil sample was prepared by "dry mixing" method (Chang *et al.* 2015b, Ayeldeen *et al.* 2017). Initially, β-glucan powder was mixed with the soil at a low moisture content of 2% by the mass ratio of the soil. It is hand-mixed with the help of pellet-knife thoroughly in a tray before adding the further required water (Latifi *et al.* 2016b, Dehghan *et al.* 2018). All the samples were then sealed in airtight plastic pouches and allowed to hydrate for two hours. The soil samples were prepared according to the specifications outlined in IS: 2720 (Part 1)-1983 and IS: 4332-(Part 1)-1967 respectively. The soil was treated with 0.5%, 1%, 1.5% and 2% of the β-glucan by the mass ratio of the soil. Distilled water was used for mixing the soil samples to avoid contamination. Soil was moulded at its respective optimum moisture content (OMC) and corresponding maximum dry unit weight (MDUW) for the unconsolidated undrained triaxial test and hydraulic conductivity tests (Latifi *et al.* 2016b, Lee *et al.* 2019). Consolidation test was carried out for soil, 0.5% and 2% β-glucan additions only. The water content of soil samples were nearer to its liquid limit for the consolidation test. Also, the samples were air-cured at an average room temperature of 33°C for periods of 7, 14 and 28 days to investigate the effect of time on strength and permeability of BGTS samples.

The experimental investigation was conducted to understand both the macro and microstructural behaviour of the BGTS samples in an effort to comprehend not only the change in geotechnical behaviour but also the mechanism that causes the change in behaviour. The Atterberg's limits (ASTM D4318-17e1), standard Proctor compaction (ASTM D698-12e2), permeability test (ASTM D5084-16a), unconsolidated undrained triaxial test (ASTM D2850-15) and One dimensional consolidation test (ASTM D2435/ D2435M-11) were investigated to understand the geotechnical properties of the treated soil. Micrographs from scanning electron microscope (SEM) and results of the surface analysis using N_2-BET were used to understand the mechanism of improvement in the geotechnical properties.

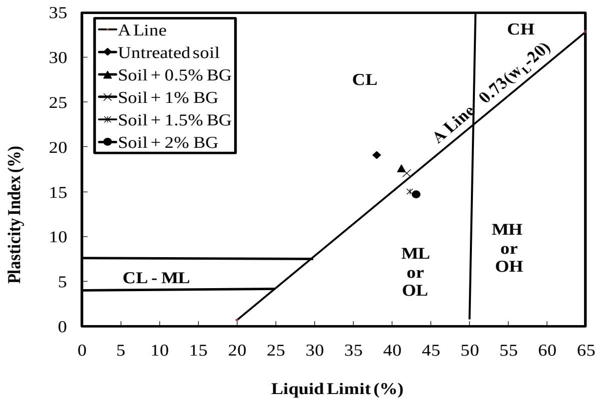
4. Results and discussion

4.1 Atterberg's limits

Consistency limits - Liquid limit (LL) and plastic limit (PL) and the plasticity index (PI) of the UTS and BGTS are shown in Fig. 3(a).



(a) Atterberg's limit



(b) Soil classification of Untreated and BGTS

Fig. 3 Atterberg's limits and plasticity chart for UTS and BGTS

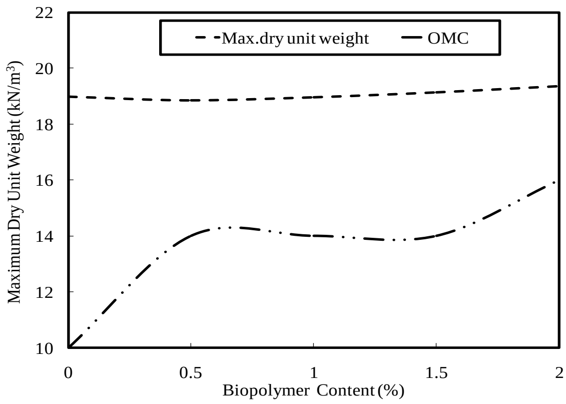


Fig. 4 Compaction Characteristics of BGTS

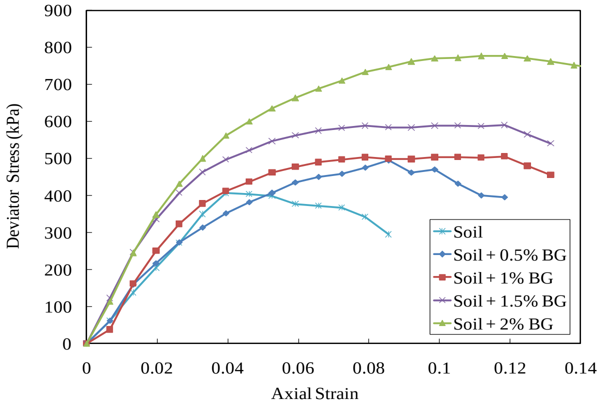
The liquid limit increased with β-glucan content. At maximum percentage of β-glucan investigated (i.e) 2 %, an increase of 1.13 times was observed. The plastic limit also mirrors a similar trend and increased from 18.90% to 28.38%. The UTS, 0.5% and 1% BGTS were classified as inorganic clay of low to medium plasticity (CL) (i.e., sandy clay or lean clay). But soil treated with 1.5% and 2% β-glucan was classified as clayey silts with slight plasticity (ML) according to UCS classification (Fig. 3b). This change is caused by the tendency of β-glucan to flocculate at higher concentrations and resist the change in compression (Chang and Cho 2014). β-glucan renders the soil less plastic due to the formation of fibres that makes the soil matrix stiffer.

4.2 Compaction behaviour

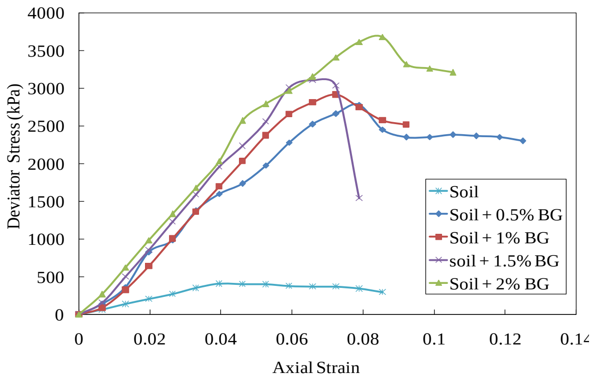
β-glucan modifies the compaction behaviour of the treated soil. The MDUW of the soil shows a marginal increase with the β-glucan content. It increased from 18.98 kN/m^3 for UTS to 19.37 kN/m^3 for soil with 2% β-glucan (Fig. 4). β-glucan causes aggregation of soil particles by the formation of hydrogen bond which leads to an increase in the dry unit weight (Chang and Cho 2014). Also, the void ratio decreases as particles tend to aggregate and voids get plugged with the addition of β-glucan. The void ratio decreases with β-glucan addition but is marginal on a further increase of β-glucan content. The OMC of the treated soil increases with an increase in β-glucan content (Fig. 4). It increases from 10% for UTS to 16% for soil treated with 2% β-glucan. OMC increased with the β-glucan content as β-glucan tends to increase the absorption of water required for the formation of hydrogels (Chang and Cho 2014). The water absorption is high at a higher concentration of biopolymer (Fig. 4).

4.3 Stress-strain behaviour

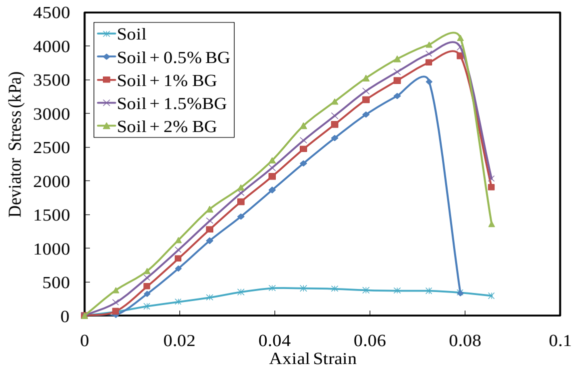
The stress-strain curves for all percentages of β-glucan treatment at all periods of curing demonstrate the stiffening of the soil matrix. Resistance to load increases with the increase in β-glucan content and the days of curing. The stress-strain behavior of the UTS and the BGTS on the 1st day (i.e., on the same day of sample preparation), 7th and 28th day respectively are portrayed in Fig. 5(a)-5(c). It can



(a) 1st Day



(b) 7th Day



(c) 28th Day

Fig. 5 Stress-strain behavior of soil and BGTS for the confining pressure of 200 kPa

be noted from Fig. 5 that the curing period influences the deviatoric stress. Deviatoric stress increases with time. A significant increase in stress is observed after 7 days of curing for all investigated percentages of biopolymer contents. There is an early gain in strength with biopolymer treatment because of the formation of fibres and ionic bonds (Chang and Cho 2012, 2014).

The increase in strength from the 7th day to the 28th day is marginal. It has been observed that the deviatoric stress increased nearly 12 times for 2% BGTS when compared to that of UTS. The stress-strain curves on the 1st day for various β-glucan content show a gradual increase in resistance to loading and also a gradual loss in post-peak strength but after 7 days of curing it shows a pronounced peak with a drastic reduction in the post-peak strength. The

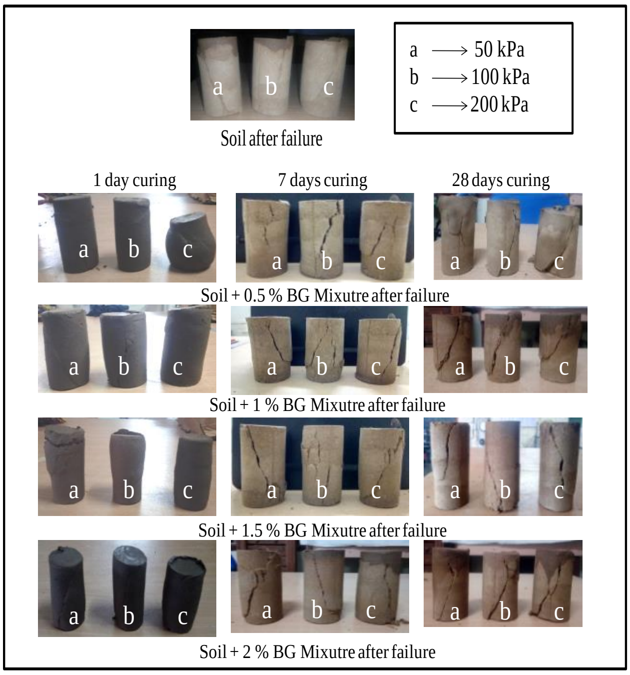


Fig. 6 Failure pattern of untreated and BGTS samples

same behaviour is more defined with the increase in days of curing from 7 to 28, though the change in peak stress is only marginal.

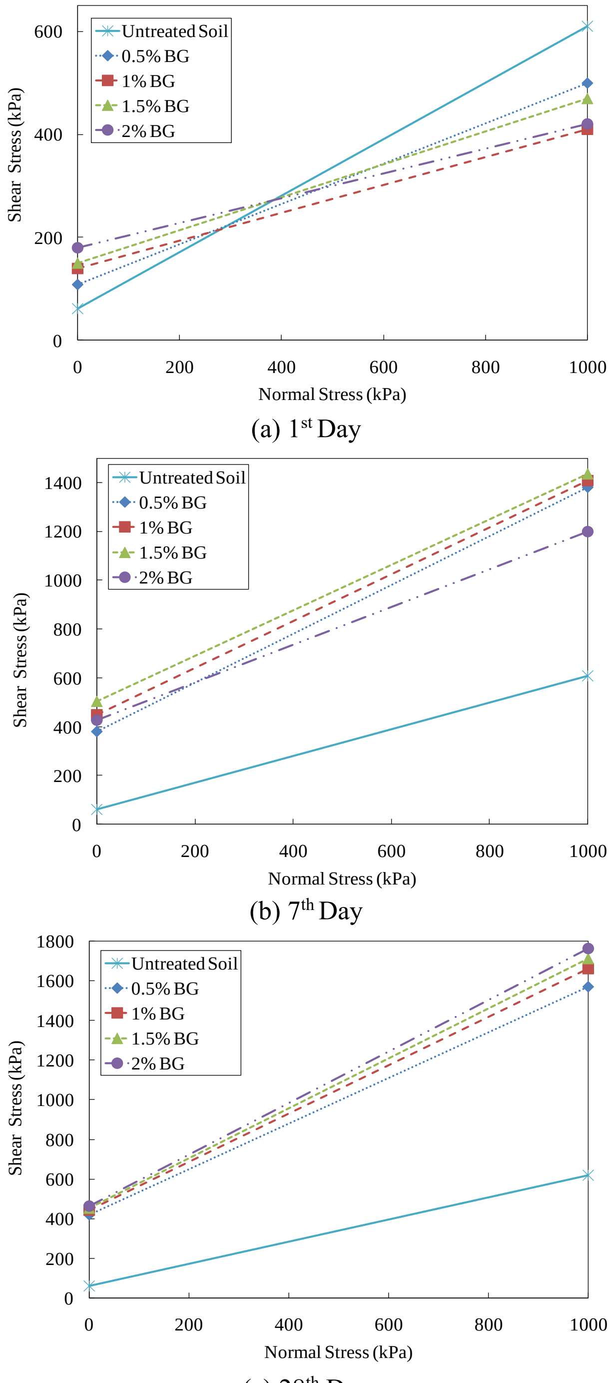
Fig. 6 depicts the failure pattern of BGTS at different confining / cell pressures (50, 100 and 200 kPa) for the various percentages of β-glucan investigated at curing periods of 0, 7, and 28 days. The BGTS samples failed by forming a rough shear plane at 0.5%, 1%, 1.5% and 2% β-glucan addition (Fig. 6). All the test specimens showed the same effect of increased brittleness after 7 days of curing and formed a shear plane across the diagonal.

4.4 Strength and mechanism

Literature shows that biopolymer treatment augments the strength of the soil significantly (Chang *et al.* 2016b, Ayeldeen *et al.* 2017). Triaxial tests conducted on soil treated with β-glucan also demonstrated a marked improvement in strength. The shear strength parameters viz. cohesion ‘c’ and friction angle ‘φ’, for various percentages of β-glucan and curing periods are shown in Fig. 7.

It can be observed in Fig. 7(a) that cohesion increases with an increase in β-glucan content but frictional resistance of the soil does not improve immediately after the addition of β-glucan. This can be attributed to the formation of hydrogels and ionic bond which inhibits the frictional resistance within the treated soil matrix. But after 7 days of curing both ‘c’ and ‘φ’ increase with the biopolymer addition as the soil particles bond together with the β-glucan fibres in a week’s time after mixing (See Figs. 7(b)-7(c)).

Figs. 8(a) and 8(b) show the effect of biopolymer content on both the ‘c’ and ‘φ’ for various curing periods (1, 7 and 28 days). Fig. 8(a) clearly indicates a significant increase in cohesion after curing for a week. There is a marginal increase in cohesion between 7 days and 28 days



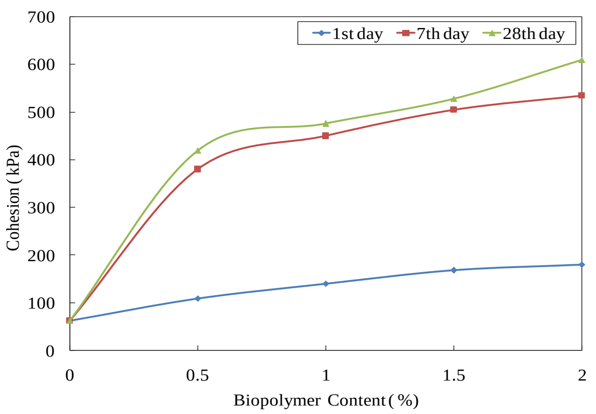
(a) 1st Day

(b) 7th Day

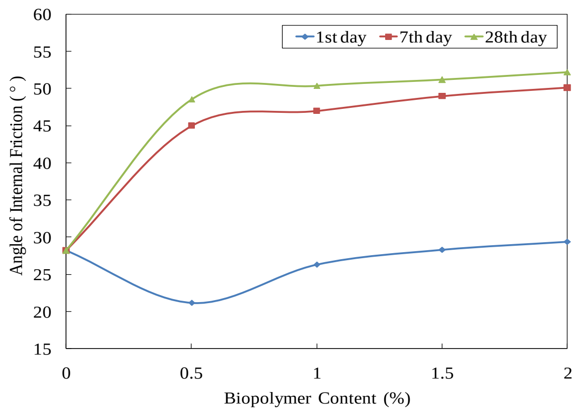
(c) 28th Day

Fig. 7 Failure envelope of untreated and BGTS

of curing. The cohesion of the UTS increased from 62 kPa to 180 kPa, 535 kPa and 610 kPa on the 1st day, after 7th day and 28th day of curing with 2% β-glucan content. This increase indicates that the soil particles bond together with the β-glucan fibres within one week after mixing (Chang and Cho 2012, 2014). After a week, the rate of bonding gradually reduces with the depletion in the β-glucan content available for reaction. A similar trend in the improvement of soil strength was also observed in the past studies (Chang and Cho 2012, 2014, Soldo *et al.* 2020) on treating Korean residual soil with β-glucan. The consistency of the soil changes from stiff to very stiff to hard with an increase in β-

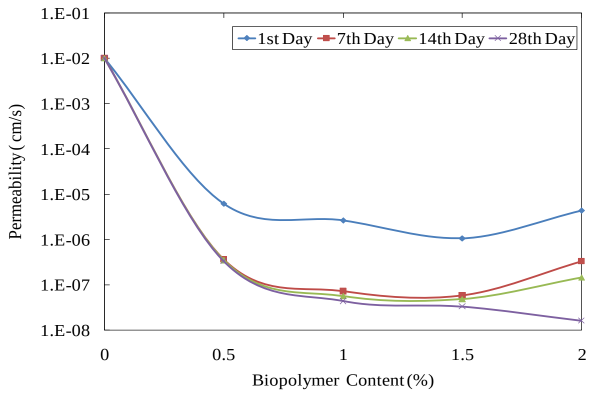


(a) Cohesion

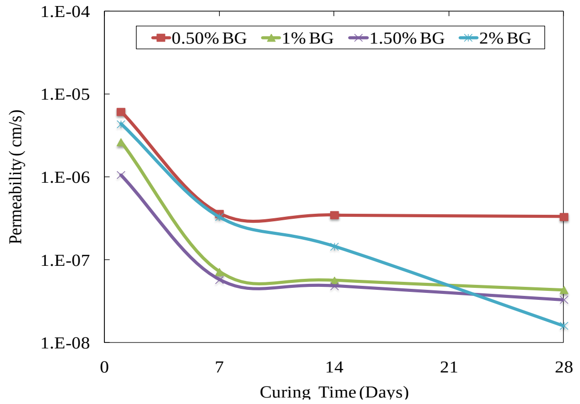


(b) Angle of internal friction

Fig. 8 Influence of biopolymer concentration and curing time



(a) Biopolymer content



(b) Curing time

Fig. 10 Effect of biopolymer content and curing time on HC

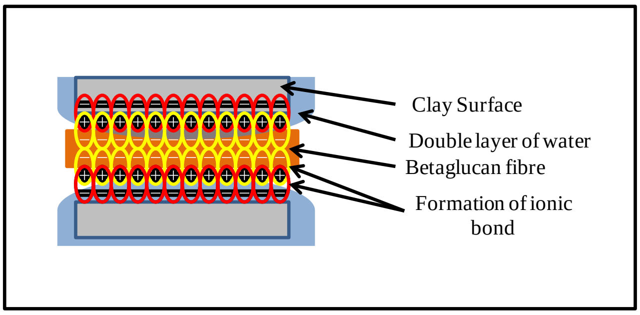


Fig. 9 Failure pattern of untreated and BGTS samples

glucan content. The same is also observed with time.

The angle of internal friction is one of the important factors that influence the shear strength of the soil. At low biopolymer content (i.e.,) at 0.5%, there is a marginal decrease in 'φ' immediately after treating with β-glucan and this can be due to coating of the biopolymer on soil particles that limits particle to particle interaction and indicates at low biopolymer contents, time is essential for complete pore plugging through formation of hydrogels. And on further addition, the quantity of biopolymer is sufficient for formation of hydrogels immediately after treatment (Kwon *et al.* 2019). Fig. 8(b) shows that there is an increase in 'φ' after one-week of curing and on further curing the increase is observed to be marginal. The increase in friction angle can be attributed to improved particle contact (Chang *et al.* 2016b). This strengthening effect of β-glucan will be useful in many field applications that require immediate strength like stabilizing cuts and walls of excavations.

The mechanism of strengthening is depicted in Fig. 9. When water is added to the dry mix of lean clay and β-glucan, strong ionic bonds are formed between the negative ions of the clay and β-glucan with the double layer of water. This bond increases the interconnection between the two soil particles and thus enhances the cohesion and angle of internal friction.

4.5 Hydraulic conductivity

HC of the BGTS shows considerable reduction due to bio-plugging of the void spaces in the soil matrix and formation of hydrogen bonds (Chang and Cho 2014, Anandha Kumar and Sujatha 2019).

4.5.1 Effect of biopolymer content

HC decreases remarkably with the increase in β-glucan content (See Fig. 10(a)) due to the plugging of void spaces in the soil matrix with β-glucan fibres (Chang and Cho 2014). A small amount of β-glucan, 0.5% (i.e., mass ratio to soil) decreases the HC of UTS from 1.03 x 10^{-2} cm/s to 6.16 x 10^{-6} cm/s (i.e., a reduction of 1673 times) after 1 day of treatment. Likewise, the HC decreases to 2.65 x 10^{-6} cm/s, 1.06 x 10^{-6} cm/s, and 4.37 x 10^{-6} cm/s with the addition of

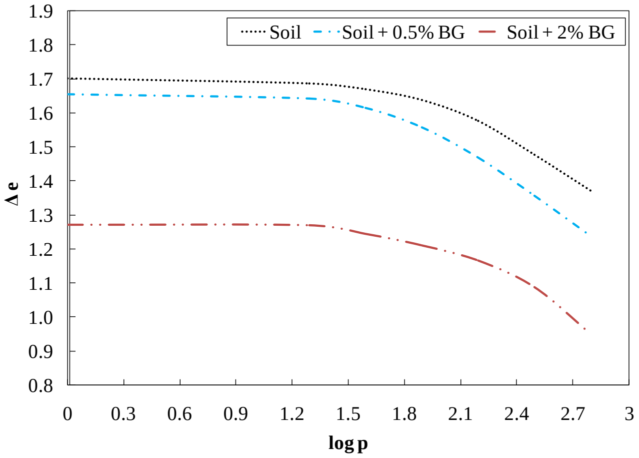


Fig. 11 e-log p curve of soil and BGTS

1%, 1.5% and 2% β-glucan respectively (i.e., 3881, 9717, and 2359 times reduction from that of soil) during the same period of investigation. The change in void ratio with the addition of β-glucan is shown in Fig. 11. The mechanism of filling the void spaces with the newly formed cementitious material can be observed in Figs. 13(a)-13(c) (i.e., higher the biopolymer content lesser will be the void spaces). This shows that BGTS samples can be used as hydraulic barriers and containment barriers (Anandha Kumar and Sujatha 2019).

4.5.2 Effect of curing time

The bio-plugging of voids is a function of time (Bouazza *et al.* 2009). This mandates the study on the effect of time on HC. When increasing the curing period, the HC decreases as shown in Fig. 10(b). There is a significant decrease in HC for BGTS after 7 days of curing irrespective of biopolymer content when compared to UTS but beyond 7 days the decrease is marginal. HC of 0.5%, 1% and 1.5% BGTS reduced for all periods of curing investigated but 2% BGTS showed an increase of 4 to 6 times in HC on the 1st day, and 7th day respectively and marginal decrease of 0.5 times after 28 days of curing when compared with the 1.5% BGTS. This shows that higher biopolymer content needs more curing time for complete void plugging. SEM micrographs (Fig. 13(a)-13(c)) demonstrate the formation of fiber bundles which become denser with time and are responsible for the decrease in HC with curing period.

4.6 Consolidation

With every load increment, void ratio (e) decreases significantly during the first thirty minutes for both untreated and BGTS and converged after 24 hours. The minimum void ratio of UTS is 1.439 and that of BGTS is 1.214. This change in the void ratio of treated soil explains the reduction in the HC of the BGTS. The coefficient of compressibility (C_c), which is a measure of compressibility, also shows a decrease with β-glucan treatment. A significant reduction in C_c is observed with the minimum β-glucan content investigated (i.e., a reduction of nearly 44% at 0.5% β-glucan addition) but the rate of change tends to reduce with a further increase (i.e., 14.8%) at 2% β-glucan addition. C_c decreases by 52% at 2% β-glucan addition indicating a substantial decrease in the compressibility (Table 2). β-glucan fibres in soil form rigid connecting matrices similar to those formed by cementitious products and thereby resist deformation (Chang and Cho 2014). The relation between e and log p (Fig. 11) clearly indicates the change in the compressibility behavior of the treated soil. The treated soil behaves like a less compressible medium showing a gradual change in void ratio with pressure. Similarly, the consolidation coefficient (C_v) decreases with the β-glucan addition indicating the change in volume and compressibility behaviour (Table 2).

Table 2 Compressibility parameters

β-glucan (%)	Compression Index (C_c)	Co-efficient of Consolidation (C_v) (cm^2/min)
0	1.340	0.198
0.5	0.754	0.185
2 .0	0.642	0.147

β-glucan treatment reduces the external surface area by pore plugging of β-glucan fibres as observed from the surface analysis carried out using an N_2-BET analyzer. This indicates the transformation of treated soil to cemented geomaterial with a flocculated structure (Latifi *et al.* 2016a).

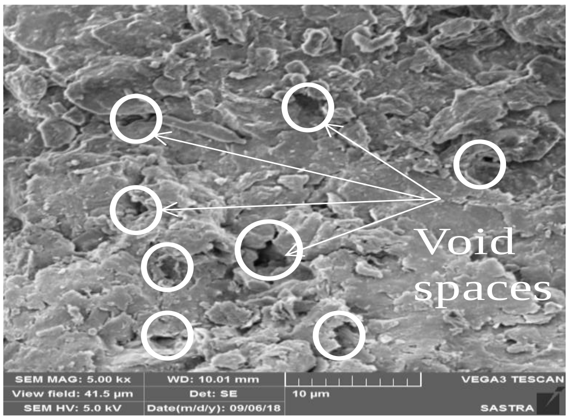
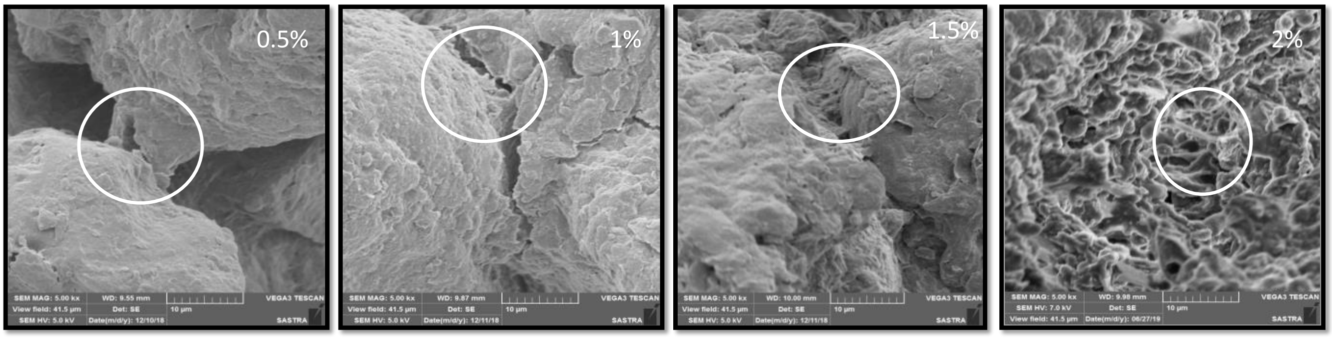


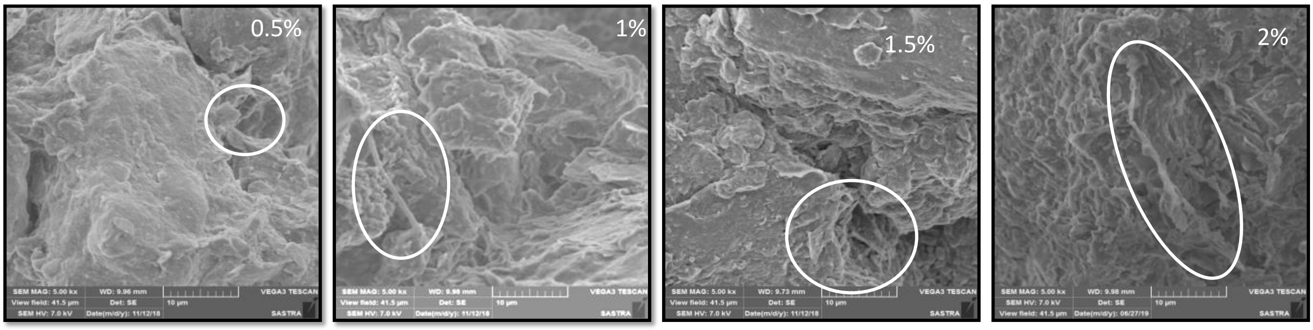
Fig. 12 UTS showing void spaces

4.7 Microanalysis

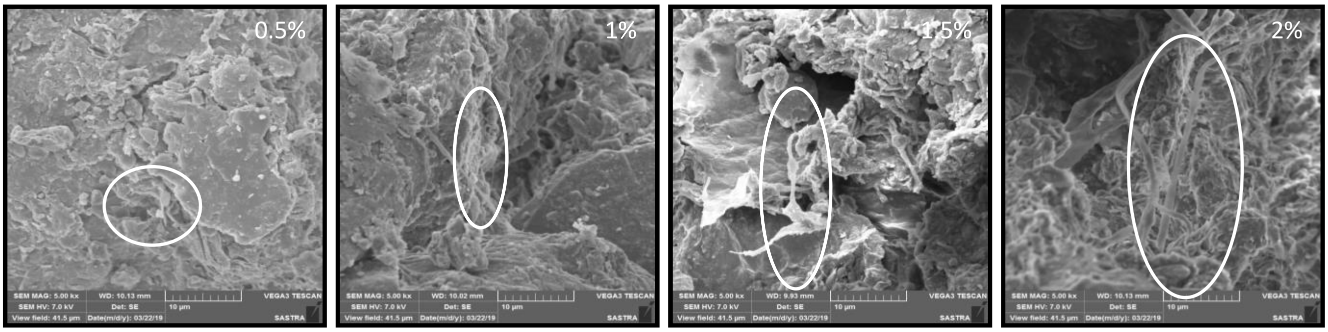
SEM micrographs of UTS and the BGTS for different periods of curing are shown in Figs. 12-13 respectively. It is seen that the soil particles are attached to the bundles of the β-glucan biopolymer in the form of fibre strands. The length of a single β-glucan biopolymer varied between 1.4 μm and 16.7 μm (Chang and Cho 2012) while the length of the UTS is 1.37 μm which is less than the size of the β-glucan. The accumulation of soil particles around the β-glucan fibre bundles as seen in Fig. 13(a)-13(c) causes an increase in the size of treated soil particles (Chang and Cho 2012, 2014). β-glucan is negatively charged (Nara *et al.* 1994, Chang and Cho 2012) and the presence of clay minerals from the XRD results confirms that the UTS surface is also negatively charged. The presence of natural cations like



(a) On the 1st day of curing



(b) After 7 days of curing



(c) After 28 days of curing

Fig. 13 SEM micrographs of BGTS

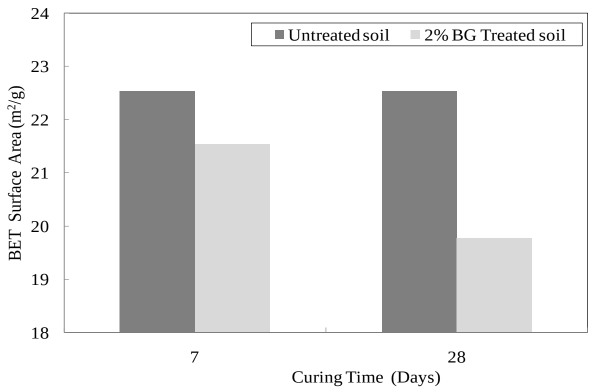


Fig. 14 N_2-BET surface area for UTS and 2% BGTS

Na^+, Mg^+, Ca^+, K^+ ions in the soil and H^+ ions from the aqueous solution attract the negatively charged surface and thus forms ionic bonds between the soil particles and the β-glucan biopolymer chains (Chang and Cho 2012). It can be noted from Figs. 13(a)-13(c) that the pores present in the soil are filled with the newly formed cementitious products in the form of gel plug and fibres which enhances the mechanical properties and thus decreases the permeability of the BGTS after 7 days and 28 days of curing.

4.8 N_2-BET analysis

Surface area analysis is indicative of the change in soil structure after the interaction (Latifi *et al.* 2016a). N_2 - BET test results of the UTS and the 2% BGTS after 7 and 28 days of curing are presented in Fig. 14. It can be noted from Fig. 14 that the surface area of the 2 % BGTS decreased with an increase in curing time. A marginal change was observed in the surface area after 7 days of curing and a substantial reduction after 28 days. This change in surface area is because of the formation of new cementitious materials that plugs pores and micropores of the soil (Latifi *et al.* 2016a). This can be seen in Fig. 13(b) and 13(c). The formation of new cementitious materials contributes to the increase in the strength of the BGTS and the reduction in HC.

5. Practical application and further scope for research

BGTS can be used as a barrier material in the landfills by replacing the conventional compacted clay liners (CCL), geosynthetics clay liner (GCL), geomembranes, etc. BGTS has an advantage over conventional liners as it addresses problems like high volume change, the formation of shrinkage and desiccation cracks in the CCL and as well as shear and puncture failure in the GCL. Because of low permeability (less than 10^{-7} cm/s) and high strength, BGTS can be used as liner materials, side and top covers in landfills. Bio-plugging of voids in BGTS also makes it an option for applications where heavy metal attenuation is required.

6. Conclusions

A comprehensive study was conducted on the effect of β-glucan on the geotechnical properties of lean clay to investigate its choice as a stabilizer. The results of the study emphasize that this biopolymer offers a sustainable option as material for chemical soil stabilization. The key advantage of using β-glucan is that it is carbon neutral, eco-friendly and does not affect the soil environment adversely. The addition of β-glucan improves the shear strength of the soil and hence can be used to improve the soil as a bearing medium and to stabilize cuts and slopes. It shows the excellent capacity to reduce the permeability of the soil and finds application as a contaminant or hydraulic barrier. The treated soil matrix is stiff and is less compressible in nature, which is yet another desirable geotechnical property particularly during construction processes. The biopolymer did not show any degradation for the observed 28 days investigation period but further studies are recommended for its long-term performance. This study is not only limited to lean clay but also has common applications in other types of soil.

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References

Anandha Kumar, S. and Sujatha, E.R. (2019), "Hydraulic conductivity of betaclucan modified soil", *Proceedings of the Indian Conference on Geotechnical and Geo-environmental Engineering (ICGGE-2019)*, Prayagraj, India, March.

ASTM (2011), *D2435: Standard Test Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading*, ASTM International, West Conshohocken, Pennsylvania, U.S.A.

ASTM (2012), *D698 - 12e2: Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort*, ASTM International, West Conshohocken, Pennsylvania, U.S.A.

ASTM (2015), *D2850-15: Standard Test Method for Unconsolidated-Undrained Triaxial Compression Test on Cohesive Soils*, ASTM International, West Conshohocken, Pennsylvania, U.S.A.

ASTM (2016), *D5084-16a: Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter*, ASTM International, West Conshohocken, Pennsylvania, U.S.A.

ASTM (2017), *D2487-17: Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)*, ASTM International, West Conshohocken, Pennsylvania, U.S.A.

ASTM (2017), *D4318-17: Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils*, ASTM International, West Conshohocken, Pennsylvania, U.S.A.

Ayeldeen, M., Negm, A., El-Sawwaf, M. and Kitazume, M. (2017), "Enhancing mechanical behaviors of collapsible soil using two biopolymers", *J. Rock Mech. Geotech. Eng.*, **9**(2), 329-339. https://doi.org/10.1016/j.jrmge.2016.11.007.

Ayeldeen, M.K., Negm, A.M. and Tawfik, A. (2014), "Using biopolymer materials to enhance sandy soil behavior", *Proceedings of the 14th International Multidisciplinary Scientific GeoConference SGEM*, Albena, Bulgaria, June.

Blanck, G., Cuisinier, O. and Masrouri, F. (2013), "Soil treatment with organic non-traditional additives for the improvement of earthworks", *Acta Geotechnica*, **9**(6), 1111-1122. https://doi.org/10.1007/s11440-013-0251-6.

Bouazza, A., Gates, W.P. and Ranjith, P. (2009), "Hydraulic conductivity of biopolymer-treated silty sand", *Géotechnique*, **59**(1), 71-72. https://doi.org/10.1680/geot.2007.00137.

Chang, I. and Cho, G. (2014), "Geotechnical behavior of a beta-1,3/1,6-glucan biopolymer-treated residual soil", *Geomech. Eng.*, **7**(6), 633-647. https://doi.org/10.12989/gae.2014.7.6.633.

Chang, I. and Cho, G. (2018), "Shear strength behavior and parameters of microbial gellan gum- treated soils: From sand to clay", *Acta Geotechnica*, **14**(2), 361-375. https://doi.org/10.1007/s11440-018-0641-x.

Chang, I. and Cho, G.C. (2012), "Strengthening of Korean residual soil with β-1,3/1,6-glucan biopolymer", *Construct. Build. Mater.*, **30**(2), 30-35. https://doi.org/10.1016/j.conbuildmat.2011.11.030.

Chang, I., Im, J. and Cho, G.C. (2016a), "Geotechnical engineering behaviors of gellan gum biopolymer treated sand", *Can. Geotech. J.*, **53**(10), 1658-1670. https://doi.org/10.1139/cgj-2015-0475.

Chang, I., Im, J. and Cho, G.C. (2016b), "Introduction of microbial biopolymers in soil treatment for future environmentally-friendly and sustainable geotechnical engineering", *Sustainability*, **8**(3), 251. https://doi.org/10.3390/su8030251.

Chang, I., Im, J., Prasidhi, A.K. and Cho, G.C. (2015b), "Effects of Xanthan gum biopolymer on soil strengthening", *Construct. Build. Mater.*, **74**, 65-72. https://doi.org/10.1016/j.conbuildmat.2014.10.026.

Chang, I., Lee, M. and Cho, G.C. (2019), "Global CO2 emission-Related Geotechnical engineering hazards and the mission for sustainable geotechnical engineering", *Energies*, **12**(13), 2567. https://doi.org/10.3390/en12132567.

Chang, I., Prasidhi, A.K., Im, J. and Cho, G.C. (2015a), "Soil strengthening using thermo-gelation biopolymers", *Construct. Build. Mater.*, **77**, 430-438. https://doi.org/10.1016/j.conbuildmat.2014.12.116.

Chen, R., Zhang, L. and Budhu, M. (2013), "Biopolymer stabilization of mine tailings", *J. Geotech. Geoenviron. Eng.*, **139**, 1802-1807. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000902.

Dehghan, H., Tabarsa, A., Latifi, N. and Bagheri, Y. (2018), "Use of xanthan and guar gums in soil strengthening", *Clean Technol. Environ. Policy*, **21**(1), 155-165. https://doi.org/10.1007/s10098-018-1625-0.

Fatehi, H., Abtahi, S.M., Hashemolhosseini, H. and Hejazi, S.M. (2018), "A novel study on using protein based biopolymers in soil strengthening", *Construct. Build. Mater.*, **167**, 813-821. https://doi.org/10.1016/j.conbuildmat.2018.02.028.

Gopika, A.S. and Mohandas, T.V. (2019), "Soil strengthening using caseinate: A protein based biopolymer", *Int. J. Res. Eng. Sci. Manage.*, **2**(2), 538-540.

Im, J., Tran, A.T.P., Chang, I. and Cho, G.C. (2017), "Dynamic properties of gel-type biopolymer-treated sands evaluated by Resonant Column (RC) tests", *Geomech. Eng.*, **12**(5), 815-830. https://doi.org/10.12989/gae.2017.12.5.815.

Ivanov, V. and Chu, J. (2008), "Applications of microorganisms to geotechnical engineering for bioclogging and biocementation of soil in situ", *Rev. Environ. Sci. Biotechnol.*, **7**(2), 139-153. https://doi.org/10.1007/s11157-007-91263.

Khachatoorian, R., Petrisor, I.G., Kwan, C.C. and Yen, T.F. (2003), "Biopolymer plugging effect: Laboratory-pressurized pumping flow studies", *J. Petrol. Sci. Eng.*, **38**(1-2), 13-21. https://doi.org/10.1016/S0920-4105(03)00019-6.

Latifi, N., Horpibulsuk, S., Meehan, C.L., Abd Majid, M.Z., Tahir, M.M. and Mohamad, E.T. (2016a), "Improvement of problematic soils with biopolymer - An environmentally friendly soil stabilizer", *J. Mater. Civ. Eng.*, **29**(2), 1-11. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001706.

Latifi, N., Horpibulsuk, S., Meehan, C.L., Majid, M.Z.A. and Rashid, A.S.A. (2016b), "Xanthan gum biopolymer: an eco-friendly additive for stabilization of tropical organic peat", *Environ. Earth Sci.*, **75**(9), 825. https://doi.org/10.1007/s12665-016-5643-0.

Latifi, N., Marto, A. and Eisazadeh, A. (2015), "Analysis of strength development in non-traditional liquid additive-stabilized laterite soil from macro- and micro-structural considerations", *Environ. Earth Sci.*, **73**(3), 1133-1141. https://doi.org/10.1007/s12665-014-3468-2.

Latifi, N., Marto, A. and Eisazadeh, A. (2016c), "Physicochemical behavior of tropical laterite soil stabilized with non-traditional additive", *Acta Geotechnica*, **11**(2), 433-443. https://doi.org/10.1007/s11440-015-0370-3.

Lee, S., Chang, I., Chung, M.K., Kim, Y. and Kee, J. (2017), "Geotechnical shear behavior of xanthan gum biopolymer treated sand from direct shear testing", *Geomech. Eng.*, **12**(5), 831-847. https://doi.org/10.12989/gae.2017.12.5.831.

Lee, S.W., Im, J., Cho, G.C. and Chang, I. (2019), "Laboratory triaxial test behavior of xanthan gum biopolymer-treated sands", *Geomech. Eng.*, **17**(5), 445-452. https://doi.org/10.12989/gae.2019.17.5.445.

Liu, J., Bai, Y., Song, Z., Lu, Y., Qian, W. and Kanungo, D. (2018), "Evaluation of strength properties of sand modified with organic polymers", *Polymers*, **10**(3), 1-15. https://doi.org/10.3390/polym10030287.

Maghchiche, A., Haouam, A. and Immirzi, B. (2013), "Use of polymers and biopolymers for water retaining and soil stabilization in arid and semiarid regions", *J. Taibah Univ. Sci.*, **4**(1), 9-16. https://doi.org/10.1016/s1658-3655(12)60022-3.

Nara, K., Shindou, T., Yada H. and Miwa, M. (1994), "Properties of β-1, 3-Glucan (Curdlan) applied for viscosity agent to concrete", *Concrete Res. Technol.*, **5**(1), 23-28. https://doi.org/10.3151/crt1990.5.1_23.

Rahar, S., Swami, G., Nagpal, N., Nagpal, M.A. and Singh, G.S. (2011), "Preparation, characterization, and biological properties of β-glucans", *J. Adv. Pharmaceut. Technol. Res.*, **2**(2), 94-103. https://doi.org/10.4103/2231-4040.82953.

Sari, Y.D. (2014), "Soil strength improvement by microbial cementation", *Mar. Georesour. Geotechnol.*, **33**(6), 567-571. https://doi.org/10.1080/1064119X.2014.953234.

Sidik, W.S., Canakci, H., Kilic, I.H. and Celik, F. (2014), "Applicability of biocementation for organic soil and its effect on permeability", *Geomech. Eng.*, **7**(6), 649-663. https://doi.org/10.12989/gae.2014.7.6.649.

Soldo, A., Miletić, M. and Auad, M.L. (2020), "Biopolymers as a sustainable solution for the enhancement of soil mechanical properties", *Sci. Reports*, **10**(1), 1-13. https://doi.org/10.1038/s41598-019-57135-x.

Swain, K. (2015), "Stabilization of soil using geopolymer and biopolymer", Master Dissertation, National Institute of Technology, Rourkela, India.

Tran, A.T.P., Chang, I. and Cho, G.C. (2019), "Soil water retention and vegetation survivability improvement using microbial biopolymers in drylands", *Geomech. Eng.*, **17**(5), 475-483. https://doi.org/10.12989/gae.2019.17.5.475.

Volman, J.J., Ramakers, J.D. and Plat, J. (2008), "Dietary modulation of immune function by β-glucans", *Physiol. Behav.*, **94**(2), 276-284. https://doi.org/10.1016/j.physbeh.2007.11.045.

Vossoughi, S. and Buller, C.S. (1991), "Permeability modification by in-situ gelation with a newly discovered biopolymer", *SPE Reservoir Eng.*, **6**(4), 485-489. https://doi.org/10.2118/19631-pa.

Wang, Q., Sheng, X., Shi, A., Hu, H., Yang, Y., Liu, L., Fei, L. and Liu, H. (2017), "β-Glucans: Relationships between modification, conformation and functional activities", *Molecules*, **22**(2), 1-12. https://doi.org/10.3390/molecules22020257.

Wiszniewski, M. and Cabalar, A.F. (2014), "Hydraulic conductivity of a biopolymer treated sand", *New Front. Geotech. Eng. GSP*, **243**, 19-27. https://doi.org/10.1061/9780784413456.003.

Zhu, F., Du, B. and Xu, B. (2016), "A critical review on production and industrial applications of beta-glucans", *Food Hydrocolloid.*, **52**, 275-288. https://doi.org/10.1016/j.foodhyd.2015.07.003.

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