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ENHANCING THE BEHAVIOR OF COLLAPSIBLE SOIL USING BIOPOLYMERS

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Abstract
This study aims to investigate the ability of using biopolymer (environmental friendly material) to enhance the mechanical characterizations of collapsible soil. Two types of biopolymers were used in this study (xanthan gum and guar gum) because of their stable behaviour under severe conditions and their availability with reasonable prices. The experimental program focused on three major soil properties, which are; compaction characterizations, collapsible potential and shear parameters, these three properties are essential in any soil improvement process. Different biopolymer concentrations were used in this study and the experimental program was performed at two curing periods (soon after mixing the soil with the biopolymer and after one week curing time). Shear parameters were measured for the treated specimens in both soaked and unsoaked conditions, while a collapsible potential test was performed under different mixing conditions (wet mix and dry mix). A numerical model was built to predict the behaviour of the treated collapsible soil after and before inundation. The analysis of results indicated the ability of both xanthan gum and guar gum to be used as soil improvement materials for collapsible soil treatment. The collapsible potential has been reduced significantly from 9% to 1% after mixing the soil with 2% biopolymer concentration in the wet case. After one week curing period, the cohesion stress has been increased from 8.5 to 105 kPa by increasing the xanthan gum concentration from zero to 2%, leading to overall improvement in the soil shear strength. Also, it proved that the superiority of guar gum over xanthan gum in improving the shear strength is about 30% more than xanthan gum at the same conditions and reduces the collapsible potential by about 20% more than xanthan gum at the same conditions.

Keywords: Collapsing soil; xanthan gum; guar gum; collapsing potential; shear strength; compaction and numerical model.
1. Introduction

Problematic soils are any unsuitable soils directly used for construction or their behavior can change with the change in environmental conditions. Collapsible soil is a metastable soil, one of wide spread problematic soils all over the world in arid and semi-arid areas, which can be recognized by its sudden volumetric reduction after increasing its humidity. The collapsible potential of the soil – the percentage of volumetric change at certain vertical stresses after and before water inundation – is a function of several factors such as; void ratio, density, soil composition and moisture content [1], [2]. Most collapsible soils are naturally wind deposited silt or sand. Loess are wind deposited collapsible soil which cover 15-20% of Europe, China and United States [3]. Responsibility for collapsible soil cohesion could be the clay particles which cover and cement the soil particles together to form what is apparently stable soil in its dry state. Some soluble materials also can be responsible for creating apparent cohesion between the soil particles such as; gypsum and calcium chloride. Collapsible soil is stable soil in its unsaturated case with a high apparent shear stress, however, under inundation conditions, the water breaks down the cementation between the particles causing large volumetric changes [4], [5].

Many methods are available in the literature to improve the collapsible soil behaviour, while choosing the appropriate method is more challenging in regards to various factors such as; collapsibility degree, economic aspects and construction aspects. Wet compaction can be effective to improve the shallow layers of collapsible soil which can be suitable for light weight structures, while injection can effectively be used for the deep improvement of heavy or underground structures. Chemical stabilization is widely using to treat collapsible soil by using several stabilizing materials such as; cement, sulfur, acrylate, and sodium silicate. Deep foundations such as piles can be used in collapsible soil by transferring the structures load to stable layers below the collapsible one. However, negative skin friction should be considered in that case[6]–[11].

Despite the great success of chemical stabilization materials in improving the behaviour of collapsible soil, it cannot be considered environmental friendly materials, as it can be toxic, modify the pH level of soil, contaminate groundwater and contaminate the soil. Moreover, cement industries are responsible for 5% of global carbon dioxide emissions, where producing of 1 ton cement is accompanied by releasing 1 ton of CO$_2$ [12]. Many environmental factors - such as the huge amount of energy consumed for production, gross water used, the contribution in global climate change and CO$_2$ emissions – made it essential to search for new environmental friendly material which can cover these aspects and be sustainable as well. Biopolymer is a sustainable carbon neutral and is always classed as a renewable material because it is made from agricultural non-food crops which can be available indefinitely. Therefore, the use of biopolymer in geotechnical engineering would create a sustainable industry[13].

Although there are various potential applications of biopolymers in geotechnical engineering, at present, the promising applications are only concentrated on bio-clogging. Bio-clogging aims to reduce the hydraulic conductivity of soil and porous rocks, which could be used to (a) reduce drain channel erosion, (b) form grout curtains to reduce the migration of heavy metals and organic pollutants and (c) prevent piping of earth dams and dikes[14]. More applications were investigated by the US Army Corps of Engineers regarding the use of biopolymers to improve slope stability on berm ranges and reduce the loss
of sediment in surface water runoff [15]. Several recent researches have studied the ability of increasing
the shear strength of soil by using biopolymer. Different types of biopolymers (such as xanthan gum, guar
gum, modified starches, agar and glucan) have been used to improve the behaviour of typical soil (sand,
silt and clay)[16]–[22]. Biopolymer showed a remarkable success in improving the soil shear strength,
however the improvement degree differs according to biopolymer type, soil types and compositions,
biopolymer doses and curing conditions. Reducing the soil permeability by using biopolymer has also been
studied previously, where biopolymer showed another success[20], [23], [24]. Despite the success of
biopolymer in improving the behaviour of typical soils, the research in using biopolymer to treat the
problematic soil is almost nonexistent. Durability of biopolymer and its economic feasibility as soil
improvement material have been discussed previously in detail in the literature [20]. Regardless the
stability of xanthan gum and guar gum which have been recorded in the literature under different severe
conditions and after curing time up to 750 days[16], more researches have to be done using some durable
biopolymer such as lignin sporopollenin. The decomposition of biopolymer after long time and with the
exposure to wet and dry cycles also should be studied as well.

This paper attempts to understand and evaluate the behaviour of two types of biopolymers on the
engineering properties of collapsible soil. Different concentrations were used in the study with two mixing
conditions (wet and dry). Compaction characterizations, shear parameters and collapsible potential are the
target parameters in this study. Also, a numerical model was built to estimate the load settlement curves
for treated soil with different biopolymer concentrations before and after inundation.

2. Materials and experimental procedures

2.1. Soils properties

To better understand the behaviour of biopolymer on the mechanical properties of collapsible soil, a
natural collapsible soil was obtained from New Borg-Alarab City, Egypt. The values of the soil physical
indices are given in Table 1, while the grain size distribution curve is presented in figure 1.

Table 1. Physical properties of the collapsible soil

<table>
<thead>
<tr>
<th>Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid limit, $LL$ (%)</td>
<td>34.60</td>
</tr>
<tr>
<td>Plastic limit, $PL$ (%)</td>
<td>19.20</td>
</tr>
<tr>
<td>Plasticity index, $PI$ (%)</td>
<td>15.40</td>
</tr>
<tr>
<td>Specific gravity, $G_s$</td>
<td>2.64</td>
</tr>
<tr>
<td>Maximum dry density, $\gamma_{md}$ (kN/m$^3$)</td>
<td>19.15</td>
</tr>
<tr>
<td>Optimum water content, $a.w.c.$ (%)</td>
<td>12.40</td>
</tr>
</tbody>
</table>
2.2. Biopolymers

Two types of biopolymers; xanthan gum and guar gum were used in this study. These biopolymers were chosen because of their availability with reasonable prices compared to other biopolymers, moreover the used two biopolymers have unique functional properties. These properties include excellent cold water dissolving, pH stability, storage stability, ionic salt compatibility and pseudo plastic flow characteristics[20].

Xanthan gum is an anionic exocellular polysaccharide produced by aerobic fermentation of sugars by the bacterium Xanthomonas campestris. The main chain of this type consists of a linear 1, 4- linked β-D-glucose backbone substituted on every two units, with a charged tri-saccharide side chain. The latter side chain is composed of a D-glucuronic acid unit linked between two D-mannose units[25].

Guar gum is a polysaccharide composed mainly of the sugars galactose and mannose. The backbone is a linear chain of β 1,4-linked mannose residues to which galactose residues are 1,6-linked at every second mannose, forming short side branches. Guar gum is more soluble than many other biopolymers and is a better stabilizer as it has more galactose branch points. In water, it is non-ionic and hydrocolloidal[26]–[28].

2.3. Specimen preparation

To prepare the treated soil specimens, the natural collapsible soil was disturbed by hand, air dried for one week and then sieved using U.S. sieve size #50. The soil water content was found to be about 3% after being air dried and before mixing the soil with the biopolymer. Two methods were used to mix the soil with biopolymer; dry mix and wet mix. The wet mix method is the main method in this study and has been used to prepare the samples for all tests. In that method, the biopolymer solution was prepared first with specific concentrations then mixed with the air-dried soil to obtain average water content of 8% ±0.1. The solution concentration was calculated as the ratio between the weight of the used biopolymer powder and the overall weight of the solution in percentage. The powder was added to the water gently to avoid clumping, then the solution was mixed until a homogeneous solution was obtained. Biopolymer concentrations of 0.25, 0.5, 1, 2, 3 and 4% were used in this study.
It was difficult to obtain a certain density for all specimens with several concentrations and various types of biopolymer as the variation in the solution viscosities will have considerable effect on the soil densities where, increasing the concentration will lead to a reduction in the density, which will be interpreted in the compaction results later. Therefore, all specimens were prepared at 75% of its maximum dry density according to their compaction characterizations as the natural density was almost about 75% of the maximum dry density.

The dry mix method was used to prepare samples which were used in the collapsible potential test, to help in studying the effect of the mixing method on the collapsible behaviour. In that method, the weight of the needed biopolymer for a certain concentration is calculated exactly same as the wet mix method and mixed directly with the air-dried soil till homogeneity. The mixture was used to prepare the required the oedometer specimens, where the water was added to the specimens during the test. All specimens were kept exposed to air after pouring in the oven at 30°C until tested, to ensure the same curing condition (humidity and temperature) for all specimens.

2.4. Test procedure

Modified Proctor compaction test was performed following the ASTM D1557-12 standard. The test was essential to determine the maximum dry density for collapsible soil and its corresponding optimal moisture content with two types of biopolymer at different concentrations.

Series of direct shear tests with 60 x 60 mm shear box were performed before and after treated the soil biopolymer using wet mix method. The test was performed according to the ASTM D3080-04 standard.

A single oedometer test was performed according to the ASTM D 5333 to estimate the collapsible potential. The vertical stress was increased gradually till a certain vertical stress of 200 kPa, where the sample was inundated with water for 24 hours. The collapsible potential was taken as the difference in the axial strain (%) at a vertical stress of 200 kPa after and before the inundation according to the specification.

3. Results and discussions

3.1. Compaction Characterization

Compaction is a primary process used in improving surface soil layers, where the soil has to be compacted to a certain density level after mixing with a stabilizing material. The achieved density after compaction will affect other mechanical characterization such as; shear strength, settlement and bearing capacity. Therefore, it was essential to study the compaction behaviour of collapsible soil mixed with different concentrations of biopolymer. The maximum dry density reduced with increasing the biopolymer concentration for both xanthan and guar gum as shown in figure 2. For xanthan gum specimens, the density reduced from 19 to 17.2 kN/m³ by increasing the concentration from zero to 2%. The reduction in
dry density was more in the case of guar gum than xanthan gum, where the density reached 16.7 kN/m³ at a guar gum concentration of 2%.

The noticed behaviour can be interpreted due to the physical characterization of both the biopolymer solution - especially the viscosity - and the soil partials weight. The light weight of the soil particles allows them to move away from each other due to the effect of the solution viscosity, which causes an overall reduction in the density as shown in figure 3. Moreover, increasing the solution concentration will increase the viscosity, which will lead to more reduction in the soil density. The higher viscosity of guar gum solution than xanthan gum at the same concentrations, represents the main reason for the superiority of guar gum in the reduction in density and increasing the corresponding water content than xanthan gum at the same concentration[20], [22].

The optimum water content was found to be increased by increasing the solution concentration. Meanwhile, the optimum water content, o.w.c increased from 12.40% for zero concentration, to 15.3% and 14.4% at a concentration of 2% for guar gum and xanthan gum respectively, which can be explained due to increasing the absorbed water used to dissolve the biopolymer by increasing the concentration.
3.2. Collapse Potential

The soil collapsible behavior has been significantly changed with changing the mixing method (wet or dry mix). The collapsible potential in this study was measured in three cases: dry mix, wet mix immediately after mix (t= 0) and wet mix after a one week curing period (t= 1 week). Figure 4.a presents the results of the collapsible potential tests for untreated collapsible soil in the three cases, while figure 4.b presents the results of collapsible potential for collapsible soil treated with 1% guar gum. The highest value of collapsible potential for untreated soil was around 15.4% for dry mix, while it was 10.3% for the wet mix (t= 0) and the least collapsible potential value was around 9% for the wet mix (t= 1 week) as shown in figure 4.a.
For guar gum treated soil, figure 4.b, the value of the collapsible potential has been reduced in all three cases. However, the biopolymer efficiency in reducing the collapsible potential is varied according to the mixing case. For dry mix, the collapsible potential was reduced from 15.44% to 4.8% with efficiency percentage in reducing the collapsible potential of 69%. While for wet mix, the efficiency percentage in reducing the collapsible potential for the wet mix was about 83.6% and 89% for $t = 0$ week and $t = 1$ week respectively. Therefore, the efficiency of the wet mix in reducing the collapsible potential is higher than the dry mix, moreover the optimum case in reducing the collapsible potential is the wet mix case after a one week curing period. This can be attributed to the swelling behavior of polysaccharide in water. For dry mix case, the swelling of the biopolymer particles in the outside layers of the specimens after wetting would reduce the permeability of the outside layer. This reduction in the permeability impedes the water from flowing inside the specimens, reducing the efficiency of dissolving the biopolymer particles inside the treated specimens [29]. On the other hand, the curing time allows these links to gain more strength thereby more resistance to collapse.

The effect of the guar gum concentration on a collapsible potential can be seen in figure 5 for a wet mix case after 1 week of curing. The guar gum concentration deeply affects the collapsible potential, even at low concentrations. The collapsible potential reduced from 9 to 3.7% with adding 0.25% guar gum concentration, while increasing the concentration from 0.25 to 1%, the collapsible potential reduced to about 1%. At a concentration of 4%, the collapsible potential almost vanished with a percentage of less than 0.1%.
Xanthan gum also had the same effect on collapsible potentials. However, the efficiency of xanthan gum is less than guar gum as seen in table 2 and figure 6. For the wet mix case after one week curing period, about 1.5% concentration of guar gum is needed to reduce the collapsible potential to less than 1% to reach a "No Problem" stage, however, this may need a 2% xanthan gum concentration to be able to reach the same stage. For dry mix, 1% guar gum concentration is needed to reach a 5% collapsible potential but again it will take about a 2% xanthan gum concentration to reach the same collapsible potential percentage. The superiority of guar gum over xanthan gum can be explained due to nature of the bonds created inside the soil matrixes. Xanthan gum produces ionic bonding between xanthan gum and the soil particles accompanying with high degree of aggregation and large voids filled with air or biopolymer gel, however guar gum formations are hydrogen bonds with less aggregation and less voids. The smaller voids and stronger hydrogen bonding contribute to the higher efficiency with the guar gum solution than that with the xanthan gum solution [20], [22].

Table 2. Collapse Potential for biopolymer treated soil with different concentrations

<table>
<thead>
<tr>
<th>Bio. Concentration</th>
<th>Collapse Potential (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry Mix</td>
</tr>
<tr>
<td></td>
<td>Xanthan</td>
</tr>
<tr>
<td>0.00</td>
<td>15.44</td>
</tr>
<tr>
<td>0.25</td>
<td>11.55</td>
</tr>
<tr>
<td>0.50</td>
<td>9.68</td>
</tr>
<tr>
<td>1.00</td>
<td>7.13</td>
</tr>
<tr>
<td>2.00</td>
<td>4.30</td>
</tr>
<tr>
<td>3.00</td>
<td>2.61</td>
</tr>
<tr>
<td>4.00</td>
<td>1.83</td>
</tr>
</tbody>
</table>
Shear strength is one of the main target parameters in soil improvement. Improving the shear strength will reflect directly on improving the soil bearing capacity, lateral earth pressure and settlement, but the problem with collapsible soil is mainly related to water, therefore, it was essential to evaluate the shear strength in soaked and unsoaked cases. The unsoaked specimens were tested in a direct shear device without changing its water content, while the soaked specimens were tested after saturation. The rate of shearing was adjusted to be 0.02 mm/min for all tests to ensure drained conditions. The shear strength parameters (including friction angle $\phi$, and cohesion $c$) of the treated soil mixes was determined from the direct shear test by plotting the failure envelope in $\tau-\sigma$ diagram as shown in figure 7. Specimens were treated with different concentrations of xanthan gum of 2%, for the unsoaked case after a one week curing time. The failure envelopes for all cases appeared to be linear with correlation coefficients $R^2$ ranging from 0.95 to 0.98. In general, all biopolymer mixtures exhibited a significant increase in shear strength compared to the untreated specimen.

**Fig.6. Effects of mixing conditions and curing times on the collapse test results for guar gum treated soil**
The friction angle after curing varied from 37° to 38.2° while it was 38.4° before treatment. It is postulated that the coating effect of the biopolymer on the grain surfaces smoothed the microscale roughness, thereby reducing the asperity interlocking of sand grains leading to a slight reduction in the friction angle [20]. Cohesion stress has been increased from 14 to 137 kPa by increasing the xanthan gum concentration from zero to 2%.

Figure 8 shows the effect of curing times on the cohesion stress of treated collapsible soil with different concentrations of both xanthan gum and guar gum. The increasing in cohesion stress after a one week curing period is clear from the figure, where the cohesion stress increased from 42 kPa directly after mixing to 105 kPa at xanthan gum concentration of 2% and from 51 to 126 kPa for guar gum specimens at
the same concentration. The cohesion stress increased after one week from 2 to 3 times comparing to its value directly after mixing for both guar gum and xanthan gum mixtures. Moreover, Guar gum mixture samples rendered higher cohesion strength than for xanthan gum treated samples at the same concentrations and curing times.

The improvement in the shear strength of the soil can be referred to by the fact that biopolymers possess various chemical functional groups, such as hydroxyl, ester or amines. Their long chain structure also provides more sites at which the characteristic chemical reactions of a given functional group can occur. Chemical bonding corresponds to the adhesive forces, whose function is to hold the soil particle and gel together at their surfaces [21]. On a microscopic scale, the effectiveness of bonding depends mainly on the type of forces present at the interface of the particle and the gel. The forces operating at such a phase interface include ionic/electrostatic or covalent bonds (chemisorption), hydrogen bonding (strong polar attraction) and van der Waals forces (physical absorption). Short range ionic/electrostatic and covalent bonds have the highest bond energy in terms of KJ/mol and therefore give the strongest bond. Van der Waals forces, which are the interaction between dipoles within the bulk material, develop the weakest bonds over a long range as shown in the SEM micrographs presented in figure 9 after Ayeldeen (2016) [20], [30]. On the other hand, solutions of viscosity usually increase as the biopolymer molecular weight increases, where the higher biopolymer molecular weight, gathers the chance of sustaining the crystallization of its macromolecule chain which leads directly to increasing the degree of crosslinking inside the soil matrix. Consequently, as the guar gum has a higher viscosity solution than xanthan gum, the guar gum mixture also has a higher shearing resistance than xanthan gum mixture as declared before in [20].

![Fig. 9. Scanning electron micrographs of the interaction mechanism between biopolymer and soil particles for: (a) xanthan gum, and (b) guar gum, after Ayeldeen (2016).](image)

To study the effect of the soaking process on the behaviour of treated collapsible soils, a direct shear test was performed twice (soaked and unsoaked) for every mixture condition. For non-treated soil, soaking the soil with water would reduce the shear strength of the soil up to 30% for compacted soil depending on water content and density [31]. For xanthan gum treated soil at a curing time of zero,
increasing the biopolymer concentration increases the cohesion stress as stated before for both soaked and unsoaked cases as shown in figure 10.a. The reduction factor between the cohesion stress for soaked and unsoaked cases (the ratio between cohesion stress in a soaked condition as opposed to that for unsoaked conditions) seems to be slightly increased with increasing the biopolymer concentration, where the reduction factor was about 10% at a concentration of 0.25% and reached 15% at 2% concentration. The effect of soaking on the cohesion stress became more clear and noticeable after one week of curing. The reduction factor in cohesion stress between soaked and unsoaked samples started at about 20% at 0.25% concentration and increased to 30% at 2% concentration.

![Cohesion stress vs Biopolymer Concentration](image1.png)

![Shear strength vs Biopolymer Concentration](image2.png)

Fig.10. Influence of soaking conditions for xanthan gum treated soil on both: (a) Cohesion stress; (b) Shear resistance at a depth of 1.5 m.

Cohesion stress is not the only factor controlling the shear strength, increasing the biopolymer concentration, causes increasing in the cohesion stress and a reduction in the friction angle. Therefore, to have...
a fair comparison about the overall shearing behaviour after treatment of collapsible soil, the total shear strength of the soil was used to compare the behaviour according to the following equation:

\[ \tau_f = c + (\sigma + \gamma h) \tan \phi \]

where \( \tau_f \) is the shear strength at point located at depth \( h \), \( c \) is the cohesion stress, \( \phi \) is the friction angle, \( \sigma \) is the external stress, and \( \gamma h \) is the over burden pressure at the point.

The shear strength has been calculated using an over burden pressure at a depth, \( h \) of 1.50m from the ground level as shown in figure 10.b. The changes in the total shear strength in functions of both cohesion stress and friction angle however, leads to a reduction in the friction angle and affects the total shear strength especially at low concentrations. The reduction factor in shear stress (the ratio between shear stress in soaked conditions than that for unsoaked conditions) for zero curing times started at 50%, at a biopolymer concentration of zero; then it was reduced linearly to 30% at 2% concentration, after 1 week of curing, the reduction factor in shear stress reduced from 50% at zero concentration to 30% at 1% concentration, however, the reduction factor started to increase again after 1% concentration to reach 35% at a concentration of 2%.

### 4. Numerical model

#### 4.1. Model description

The finite element model was built using the software *Plaxis 2D 8.2*. The used model is a concrete footing 2 m width and 0.50 m in thickness resting on 10 m layer of collapsible soil. The soil boundaries were extended horizontally for 10 m from the footings at both sides, with a total horizontal length of 22 m and it also extended 10 m under the footings. The horizontal boundary was restrained in both horizontal and vertical directions, however; the vertical boundary was restrained just in the horizontal direction and fifteen-node elements were used for both soil and footings. The model mesh was generated as a fine coarseness and then refined to be very fine to increase the nodes numbers around the footing in the affected area as shown in figure 11.
The concrete footing was modeled as a linear elastic non-porous material, which is defined by the total unit weight ($\gamma_{\text{total}}$), modulus of elasticity ($E_{\text{ref}}$) and Poisson ratios ($\nu$). The soil was simulated using the Mohr-Coulomb model by defining the soil unit weight ($\gamma$), Young’s modulus ($E$), Poisson ratio ($\nu$), cohesion stress ($C$), friction angle ($\phi$) and dilatancy angle ($\psi$). The soil shear parameters that are needed for the Mohr-Coulomb MC model were obtained from the direct shear results which were performed previously in this study - section 3.3 - for before and after inundation cases. Young’s modulus ($E$) was calculated after obtaining $E_{\text{oed}}$ - one dimensional compression modulus of elasticity - from the oedometer test before and after inundation as mentioned in section 3.2, where both $E_{\text{oed}}$ and $E$ can be calculated according to Hooke’s law as follows:

$$\frac{\partial \sigma_y}{\partial e_y}$$

$$E = \frac{(1-2\nu)(1+\nu)}{(1-\nu)} E_{\text{oed}}$$

Where $E$ is Young’s modulus, $E_{\text{oed}}$ is the oedometer modulus of elasticity and $\nu$ is Poisson ratio. The values of the numerical model parameters are listed in table 3.
Table 3. The used model parameters after and before inundation.
<table>
<thead>
<tr>
<th>Case</th>
<th>Bio. Con (%)</th>
<th>Before Inundation (unsaturated case)</th>
<th>At Inundation</th>
<th>After Inundation (saturated case)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( \gamma_1 ) (kN/m^3)</td>
<td>( E_{\text{oed}} ) (kN/m^2)</td>
<td>( E ) (kN/m^2)</td>
</tr>
<tr>
<td>Pure Soil, t = 0 week</td>
<td>0.1</td>
<td>14.82</td>
<td>10000</td>
<td>7428.57</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>15.1</td>
<td>6340</td>
<td>4709.71</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>15.15</td>
<td>5130</td>
<td>3810.86</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>15.2</td>
<td>4622</td>
<td>3433.49</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>15.25</td>
<td>4134</td>
<td>3070.97</td>
</tr>
<tr>
<td>Xanthan, t = 0 week</td>
<td>0.25</td>
<td>15.13</td>
<td>8300</td>
<td>6165.71</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>15.18</td>
<td>7700</td>
<td>5720.00</td>
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<tr>
<td></td>
<td>1</td>
<td>15.23</td>
<td>6300</td>
<td>4680.00</td>
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<td></td>
<td>2</td>
<td>15.26</td>
<td>6100</td>
<td>4531.43</td>
</tr>
<tr>
<td>Guar, t = 0 week</td>
<td>0.25</td>
<td>15.17</td>
<td>8300</td>
<td>6165.71</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>15.18</td>
<td>7700</td>
<td>5720.00</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>15.23</td>
<td>6300</td>
<td>4680.00</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>15.26</td>
<td>6100</td>
<td>4531.43</td>
</tr>
<tr>
<td>Pure Soil, t = 1 week</td>
<td>0.1</td>
<td>14.14</td>
<td>9000</td>
<td>6685.71</td>
</tr>
<tr>
<td>Xanthan, t = 1 week</td>
<td>0.25</td>
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4.2. The model phases

The model was used after that to determine the stress/displacement curves for treated soils after and before inundation, which is essential to estimate the bearing capacity of the treated soil. It was also used to calculate the settlement under a loaded footing rested on treated soil after saturation. Therefore, three phases were used in this study as shown in figure 12. The soil is separated into two zones; untreated unsaturated collapsible soil which will remain unsaturated during the three phases and the treated collapsible soil which will change from unsaturated to saturated according to the phase. Phase I is the unsaturated state where all needed parameters for the MC model were calculated in the unsaturated (dry) case and was used to study the behaviour of the treated soil without inundation (in the dry case) as represented by line AF. Phase II is the saturated state where the needed parameters were calculated after inundating the soil with water. This phase was used to understand the behaviour of the treated soil after inundation (in the wet case) as represented by line AE. Phase III is a special case for collapsing soil, where the soil is getting wet after it had been loaded, which is the case in a collapsing settlement, this collapsing settlement is caused by many problems in constructed structures on collapsible soil [32]. The behaviour of this phase can be seen in figure 12 by following the line ABCD. AB represents the unsaturated zone, where the soil had been loaded before the inundation. The behaviour in this zone will be the same as the first phase as in the unsaturated case (line AF), it can be seen from the AB and AF lines. The second zone is BC, which represents the soil volumetric shrinkage after collapsing due to inundation. The third zone is CD, which represents the saturated zone. This zone represents the soil behaviour after inundation, where it shows almost the same behaviour as the second saturated phase (line AE). To simulate zone AB and CD, the data was taken from the first unsaturated zone and the second saturated zone, respectively. However, the volumetric shrinkage after collapsing is due to inundation (line BC) and has been applied in the model as the negative volumetric strain (\(\varepsilon_v\)).

The volumetric strain was calculated from the collapsible strain (\(\varepsilon_c\)) which relates to the volumetric strain by the celebration factor \(C\) [33] as follows:

\[
\varepsilon_v = C \times \varepsilon_c
\]

where \(\varepsilon_v\) is the volumetric strain, \(\varepsilon_c\) is the collapsible strain and \(C\) is the celebration factor which was found to be 0.1 [33].

\(\varepsilon_c\) can be determined from the collapsible potential (\(C_p\)) after over burden pressure adjustment at the middle of the collapsible layer [34] as shown in the following equation:

\[
\varepsilon_c = \frac{C_p}{200} \times (\sigma + \gamma h_{mid})
\]

Where \(C_p\) is the collapsible potential from a single oedometer test (%), \(\sigma\) is the external stress from the footing (kPa), and \(h_{mid}\) is the over burden pressure at the middle of the treated collapsible layer (kPa).
Fig. 12. Schematic diagram of the used phases in the analysis

The model has been verified by comparing the numerical outcomes with two field test results obtained from plate load test on collapsible soils after Ali (2015) and Shalaby (2014) and it was noticed that there is a good compatibility between the field test and the numerical model, which confirms the ability of using the model to predict the behaviour of collapsible soils [35], [36].

4.3. Effects of inundation on pressure settlement curves

The effect of inundation on both untreated and treated collapsible soil can be seen in figure 13, where the pressure settlement is drawn for untreated collapsible soil and xanthan gum treated soil with a concentration of 2% cured for 1 week after and before water inundation. The ultimate bearing capacity \( q_{ult} \) has been calculated from the intersection between the initial tangent and the steeper tangent to each curve [37]. It is observed from the figure that, \( q_{ult} \) for untreated soil was reduced by 67% due to the inundation effect (from 158 to 106 kPa). However, treatment of the soil with xanthan gum increased \( q_{ult} \) by 700% (from 158 to 1116 kPa).
Fig. 13. Effects of inundation on pressure settlement curves for untreated soil and xanthan gum treated soil with a concentration of 2% after 1 week of curing time.

The reduction in bearing capacity due to water inundation on the treated soil was less than for untreated soil, where $q_{ult}$ for treated soil was reduced by 81% after inundation (from 1116 to 900 kPa). This can be explained due to the reduction in permeability after treating the soil with biopolymer, which obstructs the flow of water inside the soil pore holes thereby reducing the effect of inundation. The crosslinks inside the soil gaps which formed by the biopolymer could also improve the bearing capacity after inundation. However, the improvement in shear strength parameters is the mainly responsible for the improvement in bearing capacity before and after treatment.

4.4. Effects of concentration on the collapsible settlement (Phase III)

Fig. 14. Load settlement curves for guar gum treated soil after 1 week of curing time.
Figure 14 displays the load settlement curves for collapsible soil treated with guar gum during inundation after 1 week curing period. The results were obtained from the numerical model using Phase III to study the effects of biopolymer concentrations on the load settlement curve. It can be noticed that increasing the concentration remarkably reduces the displacement during and after inundation, where using guar gum concentrations of 2% reduced settlement during inundation from 0.22m to 0.05m.

![Graph showing load settlement curves for different biopolymer concentrations.](image)

For a clearer understanding of the effects of inundation on settlement under footings, figure 15 shows the effect of both guar gum and xanthan gum on a settlement of a 2m width footing loaded with a concentration load of 250 kN as estimated from phase III in the numerical model. From the figure, it can be seen that the efficiency of biopolymer increased remarkably by increasing the biopolymer concentration, where increasing the concentration reflected directly to a reduction in settlement. However, this reduction in settlement became less effective after increasing the concentration from 1 to 2%. This can be explained due to the combined effect of biopolymer on the soil shear strength, where increasing the biopolymer concentration will help in increasing the soil cohesion, the soil elasticity will be reduced because of increasing the concentration.

The efficiency of guar gum is clearly higher than xanthan gum in resisting settlement during inundation regardless of the curing time. This can be interpreted due to the higher molecular weight of guar gum compared to xanthan gum, where increasing the molecular weight reflects directly to high growth in the accumulation of crosslinking between particles, followed by a high reduction in permeability[20]. This reduction in permeability will work on impeding the seepage inside the soil matrix, which will reduce the effect of inundation in the case of guar gum other than xanthan gum mixtures. The efficiency of biopolymer appears to be acceptable in reducing the settlement even without a curing time, however, after a one week curing period, the efficiency of using biopolymer becomes more valuable.
4.5. Soil bearing capacity

Ultimate bearing capacity ($q_{ult}$) is the maximum stress that the soil can support before the shear fails and by dividing $q_{ult}$ by factor of safety, the allowable bearing capacity ($q_{all,shear}$) can be calculated. However, in some types of soils which are expected to serve a large settlement or in some other kind of structures where it is required to control the settlement to a certain value; in these cases, the allowable bearing capacity ($q_{all,sett}$) can be considered according to the required settlement. Overall, the considered allowable bearing capacity ($q_{all,considered}$) is governed by both soil failure and allowable settlement—the least of $q_{all,shear}$ and $q_{all,sett}$. Two methods were used to estimate the allowable bearing capacity from load settlement curves; in the first method, the ultimate bearing capacity was calculated from the intersection between the initial tangent and the steeper tangent, then the allowable bearing capacity $q_{all,shear}$ was calculated using a factor of safety with a value of 3.0 [37], while in the second method, the allowable stress $q_{all,sett}$ at 10 cm settlement was obtained, as shown in figure 16 for treated soil before and after inundation.

For non-treated soil before or after inundation, $q_{all,shear}$ is almost 50% less than $q_{all,sett}$. Therefore, it can be taken as the considered allowable bearing capacity ($q_{all,considered}$). With increasing the concentration, both $q_{all,shear}$ and $q_{all,sett}$ have to be increased, however, the percentage of increasing $q_{all,shear}$ was much lower than $q_{all,sett}$.
higher than $q_{all,sett}$. $q_{all,shear}$ by about 600% by increasing the concentration from 0 to about 2%, while $q_{all,sett}$ increased by a percentage of about 200%. This can be interpreted due to enhancing the shear parameters by increasing the concentration which will lead to an increase in $q_{all,shear}$. At the same time, increasing the biopolymer concentration may lead to a reduction in the modulus of elasticity of the treated soil [20], which may interpret the superiority of increasing $q_{all,shear}$ than $q_{all,sett}$. The gap between $q_{all,shear}$ and $q_{all,sett}$ started to shrink with increasing the biopolymer concentration until a certain concentration value was reached, this value differs according to the soil inundation state, where $q_{all,shear}$ and $q_{all,sett}$ becomes equal. After that, the value of $q_{all,shear}$ becomes higher than $q_{all,sett}$ at the same concentration. Saturated treated soil (after inundation), $q_{all,considered}$ is mainly controlled by $q_{all,sett}$, except in the case of light concentrations (less than 0.5%), where the inundation will increase the soil elasticity, increase the settlement and reduce the allowable bearing capacity. However, in cases of unsaturated soil (before inundation), $q_{all,considered}$ is equally effected by both $q_{all,shear}$ and $q_{all,sett}$ according to the concentration, as 1% concentration is the critical value where the behaviour changes before and after from $q_{all,shear}$ to $q_{all,sett}$ respectively. With changing the required settlement value or the factor of safety, the critical point may be moved. Therefore, it is necessary to check both $q_{all,shear}$ and $q_{all,sett}$ especially for concentrations around the critical point (almost in the range of 0.5 to 1.5%).

5. Conclusions

Within the experimental range of this investigation, the following conclusions can be stated:

- The dry density reduces with increasing the solution concentrations for both guar gum and xanthan gum from 19 to about 17 kN/m$^3$ while the optimum water content increased from 12% to around 14.6%.
- Biopolymer has proved highly efficient in reducing the collapsible potential for both wet and dry mixing conditions. The efficiency of biopolymer for the wet mix was about 2-3 times more than dry mixing. Therefore, the current study suggests using the wet mix technique to treat collapsible soils rather than dry mix.
- Mixing the soil with 2% biopolymer concentration leads to a reduction in the collapsible potential from 9% to about 1%.
- Despite the reduction in density, which was observed with increasing the concentration, the shear resistance of the treated soil has improved. The cohesion stress has increased by increasing the concentrations with a slight reduction in the friction angle. However, the total shear stress has increased with increasing the concentrations for both guar gum and xanthan gum.
- Guar gum showed superiority over xanthan gum for increasing the soil cohesion stress and reducing the collapsible potential with a percentage of about 20%.
- From the numerical model it can be concluded that:
  a. Treating the soil with biopolymer will improve the soil bearing capacity and will also reduce the effects of inundation.
  b. Increasing the biopolymer concentration leads to reducing the settlement during and after inundation under the footings.
c. For treated soil after inundation, $q_{all,sett}$ can be used as the considered allowable bearing capacity, especially for biopolymer concentrations higher than 0.5%. However, for treated soil before inundation, it is suggested to calculate both $q_{all,sett}$ and $q_{all,shear}$ before estimating the considered allowable bearing capacity.

References


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