Experimental Study of the Usage of Combined Biopolymer and Plants in Reinforcing the Clayey Soil Exposed to Acidic and Alkaline Contaminations

Jing Ni 1,2, Jiaqi Chen 1, Shuojie Liu 1, Ganglai Hao 1 and Xueyu Geng 2,*

1 Department of Civil Engineering, University of Shanghai for Science and Technology, Shanghai 200093, China; jing.ni.1@warwick.ac.uk (J.N.); 203642089@st.usst.edu.cn (J.C.); 213382213@st.usst.edu.cn (S.L.); 193791872@st.usst.edu.cn (G.H.)
2 School of Engineering, University of Warwick, Coventry CV4 7AL, UK
* Correspondence: xueyu.geng@warwick.ac.uk

Abstract: In the last decade, biopolymers have been extensively studied, showing a great potential in soil reinforcement and the promotion of vegetation growth with limited environmental impact. In this paper, a soil reinforcing method with combined biopolymer (xanthan gum, XG) and plants (oat) was proposed to strengthen the clayey soil with different pore fluid pH values. A series of laboratory tests were conducted, mainly including the plant cultivation tests and the direct shear tests. It was found that oats grew better in the neutral, weakly acidic, and weakly alkaline soil environments. Both 0.25% XG and 0.50% XG that mostly promoted plant growth, also led to higher soil shear strength. An excessive XG content (e.g., 0.75% and 1.00%) may lead to the formation of a hard XG–soil matrix, preventing oat growth and therefore resulting in a lower shear strength. The XG–oat combination was found to be more effective in treating the soils with acidic pH values. Furthermore, the XG–oat combination is able to reduce the types and contents of heavy metal elements in the soil. Therefore, we suggest using biopolymers in combination with plants to improve the stability and geotechnical performances of the shallow soil slopes that are exposed to acidic and alkaline contamination.

Keywords: xanthan gum; oats; clayey soil; acidic/alkaline contamination; direct shear test

1. Introduction

In the last decade, a new type of soil reinforcement material biopolymer, which is environmentally friendly and quick-acting, has been gaining an increasing opportunity to be used in the field of geotechnical engineering [1–6]. Biopolymer-based soil treatment technology is used to improve the geotechnical properties of soils by adding plant or microbial secretions, as well as some artificially synthesized organic polymers to the soil [7]. The viscous biopolymer hydrogels can improve soil cohesion immediately after being mixed with soils through cementation [8]. When the biopolymer hydrogels are dehydrated and converted to rigid fibers, the compression and shear strength of the treated soils can be further improved [9–11]. Since biopolymers have high specific surface area with surface charges, they are able to bind directly to clay particles through ionic and hydrogen bonds, resulting in an efficient soil enhancement [8,12].

Soil reinforcement with vegetation is also deemed to be a sustainable and cost-effective method for stabilizing shallow soil slopes. While plant roots are able to provide direct mechanical reinforcement through the aggregation of rhizosphere soil in close proximity to the roots [13–16], the plant transpiration that discharges water from the soil through transportation pathways (i.e., from roots to leaves) also increases the matrix suction, thus...
enhancing the soil stability [17–20]. However, soil stabilization using vegetation is always faced with the problem of insufficient water supply [21,22].

According to Chang et al. [23], soils treated with biopolymers (e.g., β-glucan and xanthan gum) lead to promoted germination and growth of oats, probably owing to the enhanced water retention capacity of the biopolymer-treated soils. Tran et al. [24] later reported that β-glucan is able to increase the vegetation’s survivability in severe drought environments (i.e., arid and semiarid regions) because β-glucan not only helps to reserve water in the soil, but serves as a nutrient for plant metabolism as well, thereby increasing the resilience of vegetation to the extreme environmental conditions. As biopolymers contribute to both soil strength enhancement and vegetation growth promotion, their usage is expected to increase the efficiency of soil slope reinforcement with vegetation, especially at the initial stage of vegetation growth when the plant roots are not well developed and are more vulnerable to the variation in water supply. In this context, Ni et al. [25] carried out a study to test the feasibility of using a biopolymer–plant soil reinforcing method for improving a clayey soil, by examining both the vegetation growth in the biopolymer-treated soil and the shear strength of the vegetated soil (with biopolymer). The results indicated that the biopolymer (i.e., xanthan gum) can improve the water-holding capacity and fertility of the soil, and therefore increase the root content per unit of soil. In addition, in either the early stage of seed germination or later stage of root growth, the shear strength of the soil reinforced with the biopolymer–plant combination is superior to that treated with the single method (i.e., biopolymer treatment or planting vegetation). Therefore, the usage of combined biopolymer and plants seems to be a desirable alternative for soil slope stabilization. Hitherto, the performance of the biopolymer–plant soil reinforcing method has not been examined in acid- and alkali-contaminated soils. When the soil is eroded by acidic or alkaline pollutants (e.g., acid rain, industrial wastewaters, etc.), its physicochemical and mechanical properties change accordingly, in terms of Atterberg limits [26–28], compressibility [29,30], and mechanical strength [26,27,31–35].

This study aims to expand the application of the biopolymer–plant combination to clayey soil exposed to acidic and alkaline contaminations. Xanthan gum (XG) and oat are used in combination for soil improvement. XG is a polysaccharide biopolymer obtained by synthesizing glucose or sucrose by a cabbage plant bacterium (Xanthomonas campestris) [36]. It consists of two glucose, two mannose, and one glucuronic acid units [37]. The structural characteristics of XG (i.e., rigid chain helical structure) lead to its stable physicochemical properties, showing high stability over a wide range of temperatures, pH values, and electrolyte concentrations [7]. Due to XG’s good physicochemical properties, abundant content in nature, and relatively mature production technology, XG is widely used in biochemical medicine, beverages and food, oil exploration, agricultural development, and other fields [37,38]. Recently, XG has been recognized as one of the biopolymers that works superiorly with soils [39–43]. In the meantime, the cost of XG has been decreasing year by year [37]. Oats are the sixth largest cereal crop used as food, feed, and forage worldwide [44], and are predominantly grown in developed countries, e.g., Canada and the United States of America [45]. They are also popular in most developing countries, e.g., Russia and China [45,46]. Oats have tenacious vitality with high resistance to varying temperature, drought, salt ion, barren, etc., and the germination rate of oat seeds is relatively fast, e.g., 48 h after sowing [47–50]. In addition, the oat roots are erect, which can represent the root structure of most plants in the early growth stage [51].

By conducting the vegetation cultivation tests in the XG-treated soil and direct shear tests on the vegetated soil (with XG), the impacts of increasing the content of XG added to the soils with different pore fluid pH values on both the oat germination and soil shear strength are explored. The soil strengthening mechanism of the XG–oat combination is investigated and the potential of the proposed method for enhancing the geotechnical performances of the soil slopes exposed to acidic and alkaline contaminants is demonstrated.
2. Materials and Methods

2.1. Clayey Soil

The clayey soil obtained from Shanghai, China was used in this study. Tested by the Mastersizer 2000 particle size analyzer (Malvern, UK), the particle gradation curve of the clayey soil was obtained and is shown in Figure 1. The soil is made up of sand, silt, and clay with 14.9%, 74.1%, and 11.0% weight content, respectively. The soil properties are liquid limit \( w_l = 38.5\% \), plastic limit \( w_p = 24.3\% \), optimum moisture content OMC = 21.9%, specific gravity \( G_s = 2.7 \), \( D_{50} = 0.03 \text{ mm} \), and pH = 7.2. As per ASTM D2487, the clayey soil was therefore classified as lean clay (CL).

![Grain-size distribution curve](image)

Figure 1. Grain-size distribution curve.

X-ray fluorescence spectrometer (XRF) is an instrument that can perform rapid, simultaneous determination of multiple elements. Under the excitation of X-rays, the inner electrons of the atoms of the detected element undergo energy level transitions and emit secondary X-rays (i.e., X-fluorescence). In this study, the X-fluorescence spectrometer ARL ADVANT’X IntelliPower TM 4200 (ThermoFisher Company, USA) was used to test the soil chemical elements and composition. The XRF results indicated that the most abundant elements are Si, O, Fe, Ca, Al, Mg, K, and Na. Compounds such as SiO\(_2\) (58.68%), Al\(_2\)O\(_3\) (13.51%), CaO (7.47%), and FeO (7.44%) have the highest concentrations.

2.2. Acidic and Alkaline Solutions

Artificial acidic and alkaline pollutants were prepared by diluting sulfuric acid solution with a concentration of 98.08% and sodium hydroxide solution with a concentration of 0.5039 mol/L with distilled water, respectively. The solutions were adjusted to different pH values of 2, 5, 7, 9, and 12. A pH-meter (Shanghai Yueping PHS-3C, Shanghai, China, accuracy ±0.01) was used to perform the pH measurements.

2.3. Biopolymer

XG was utilized as the soil-reinforcing bio-binder in the current study for its good functional properties and reasonable price as previously demonstrated. The XG powder for this study was manufactured by Shandong Fengtai Biological Technology Co., Ltd (Jin nan, China).

2.4. Plant

Oats were chosen as the target plant for soil reinforcement and were cultivated originally from seeds in the current experiment.
2.5. Experimental Scheme and Sample Preparation

The experimental program involved exploring the behaviors of the acidic- and alkaline-contaminated clayey soils with and without the treatment of XG–oat combination through five aspects: (1) Atterberg limits; (2) plant growth; (3) mechanical properties under direct shear; (4) microscopic structures; (5) heavy metal element contents. The soil and treatment conditions for some of the tests are provided in Table 1. The following subsections present the test procedures for each component of the experimental program. Each test was replicated at least three times to achieve a reliable average.

Table 1. Soil and treatment conditions for Atterberg limits, plant cultivation, and direct shear.

<table>
<thead>
<tr>
<th>Tests</th>
<th>Pore Fluid pH Values</th>
<th>Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atterberg Limits</td>
<td>2, 5, 7, 9, 12</td>
<td>None</td>
</tr>
<tr>
<td>Plant cultivation</td>
<td>2, 5, 7, 9, 12</td>
<td>0.00% XG–oat, 0.25% XG–oat, 0.50% XG–oat, 0.75% XG–oat, 1.00% XG–oat</td>
</tr>
<tr>
<td>Direct shear</td>
<td>2, 5, 7, 9, 12</td>
<td>None, 0.00% XG–oat, 0.25% XG–oat, 0.50% XG–oat, 0.75% XG–oat, 1.00% XG–oat</td>
</tr>
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2.5.1. Atterberg Limits Test

The oven-dried and pulverized clayey soil (i.e., base soil) of 300 g each was placed into the 1 L solution with pH values of 2, 5, 7, 9, and 12, respectively. The base soil was allowed to soak in the pollutants for a short period, after which the contaminated soil was taken out, oven dried, and pulverized. The Atterberg limits test was carried out in accordance with GB/T 50123-2019 (Ministry of Water Resources of the People’s Republic of China, 2009). A cone with a mass of 76 g and a tip angle of 30° was released and penetrated into a soil sample (55 mm diameter and 40 mm height). The penetration depth of the cone was measured 5 s after release. For each pH value, three samples with increased moisture contents were tested. The moisture contents corresponding to 17 mm and 2 mm penetration depth determined with a linear fitting curve in the cone penetration–moisture content relationship (in log scale) were liquid limit and plastic limit, respectively.

2.5.2. Plant Cultivation Test

Dry XG powder (with 0.00%, 0.25%, 0.5%, 0.75%, 1.00% of base soil mass) was mixed with the base soil. Then the designated amount of solution (mass of dry XG–soil mixture × optimum moisture content) with different pH values (2, 5, 7, 9, and 12) was poured into the dry XG–soil mixture. A homogeneous wet XG–soil mixture was obtained finally through a thorough mix. The wet mixture was then placed into a cultivation box (length × width × height = 205 mm × 150 mm × 80 mm, respectively, see Figure 2a), covered with a filter paper and statically compacted with a wood panel. After compaction, the filter paper and wood panel were removed, and 160 oat seeds were evenly sown on the soil surface, see Figure 2b. A thin layer of the mixture (e.g., 1 cm) was placed on top to cover the oat seeds (Figure 3). Compaction degree of 80% was adopted to take into account the requirements for both soil stability and root growth space [25].

A soil moisture sensor was installed in the vegetated soil to measure the soil volumetric moisture content, as shown in Figure 3. The instrument uses FDR (Frequency Domain Reflected Electromagnetic Pulse) technology for measurement, which has smaller error (±1%), more sensitive response, and higher stability than the traditional capacitive measurement. The volumetric moisture content and the number of germinated oat seeds in the cultivation box were measured and recorded every 24 h for a period of 14 days. Watering was performed by providing designated amount of water (i.e., 70 mL) in 5 s on the 1st, 2nd, and 3rd days and the 8th, 9th, and 10th days after sowing to meet the moisture conditions required for the initial growth of oats and the rainfall conditions in the oat growing areas in China [25]. During the test, the indoor constant temperature was kept at 25 °C and the relative humidity was 75%.
2.5.3. Direct Shear Test

After the plant cultivation test (i.e., at the end of the 14th day), the seedlings of the plants were cut off with scissors. Three positions with relatively uniform seed germination were selected and a cutting ring was used to take out the sample from the cultivation box, see Figure 4a. Then scissors and knife were used to carefully remove the soil above and below the cutting ring to prepare the sample for the direct shear tests, see Figure 4b. The samples were subjected to the direct shear test under the overburden stresses of 50, 100, and 150 kPa, respectively, and the shear rate was 0.8 mm/min. In the test, the overburden stresses of 50, 100, and 150 kPa were selected to represent the soil weight above the penetration depth of the plant root system [52–54]. The direct shear test was carried out in accordance with the standard geotechnical testing method (GB/T 50123-2019, China).

2.5.4. Scanning Electron Microscope (SEM) Analysis

Scanning electron microscope (SEM) analysis can be used to explore the microstructural characteristics of soils (e.g., shape, size, and aggregation of soil particles). In this study, SEM images were taken for both uncontaminated and acid-contaminated soils. Microstructural analysis was conducted to better understand the underlying mechanisms of the degradation in the geotechnical properties of the clayey soil exposed to acidic pollutants.
3. Results and Discussion

3.1. Acid- and Alkali-Contaminated Soils

3.1.1. Atterberg Limits

The results of the liquid and plastic limits for the soils contaminated with solutions of different pH values are shown in Figure 5. For the alkali-contaminated soil, the liquid limit and plastic limit increased with the increasing pH value. For the acid-contaminated soil, the plastic limit increased with the increasing pH value, while the liquid limit had an opposite trend. The changes in the thickness of the diffuse double layer of clay fraction may describe the mechanism of the effect of different pH values on the Atterberg limits [55–57]. As the alkaline pH increased, the diffusion layer became thicker, leading to the increase in the liquid and plastic limits of the alkaline-contaminated soils [26,57]. When the soil was exposed to the acidic pollutant, H+ ions would probably replace the commonly found exchangeable cations (i.e., Na+, Ca++, Al3+, and Fe3+) from the diffuse double layer of the clay particles, leading to the increase in the double layer thickness [58,59] and, hence, the increase in the plastic limit. However, the liquid limit of the acidic soil decreased gradually with the decrease in pH value. This may be due to the fact that the free oxides and cemented minerals in the soil were gradually corroded by the sulfuric acid solution, resulting in the formation of a loose soil structure [59,60]. This process brought down the interparticle shearing resistance and had the tendency to decrease the liquid limit [61]. Compared with the increasing trend of the liquid limit caused by the increase in the diffuse double layer thickness, the decreasing trend of the liquid limit caused by the decrease in the interparticle shearing resistance might dominate, which ultimately led to the decrease in the liquid limit of the acid-contaminated soil.

Figure 5. (a) Liquid limit; (b) plastic limit of the acid- and alkali-contaminated soils.

3.1.2. Direct Shear Test

Figure 6 presents the relationship between shear stress and shear displacement of the acid- and alkali-contaminated soils at different overburden stresses (i.e., 50, 100, and 150 kPa). The results indicate that the acid-contaminated soils had lower shear stress-displacement curves than the uncontaminated soil (i.e., pH = 7) and alkali-contaminated soils. As mentioned previously, the clayey soil contained Al2O3 with a concentration of 13.51% and Fe2O3 with a concentration of 7.44%. When the clayey soil was polluted by the acidic solution, a reaction between the acid (i.e., H2SO4) and the oxides in the soil (i.e., Fe2O3 and Al2O3) occurred, leading to the generation of Fe(SO4)3 and Al2(SO4)3. The newly generated substances could dissolve in the solution and flow out of the soil [27,62], resulting in the reduction in the solid phase composition and the formation of a loosened soil structure [59,60]. Figure 7 shows the SEM images of the uncontaminated soil (i.e., pH = 7) and the
soil contaminated with the acidic solution (i.e., pH = 2). It is confirmed that the acid-contaminated soil became more porous (Figure 7b,d) compared with the uncontaminated soil (Figure 7a,c), due to the corrosion of oxides and cemented minerals in the soil with the progress of the chemical reaction [27].

Compared with the acid-contaminated soil, the shear strength values of the alkali-contaminated soils did not reduce so much (e.g., at overburden stress = 150 kPa) and even increased (e.g., at overburden stress = 50 and 100 kPa). This might be attributed to the pH-dependent nature of the charges on the exposed edges of clay particles. According to [33], when the pH value is low, particle edge charges become increasingly positive due to the adsorption of H\(^+\) ions and, conversely, more negative at high pH values due to the adsorption of OH\(^-\) ions [33]. As a result, edge-to-face (E-F) associations tend to dominate interparticle binding in the acidic pH environment [32], while the face-to-face (F-F) associations prevail in the alkaline pH environment [58]. Therefore, the increased shear strength of the alkali-contaminated soil might be due to the formation of the face-to-face clay particle associations [26].

![Figure 6](image-url). Relationship between shear stress and shear displacement of the acid- and alkali-contaminated soils under overburden stresses of (a) 50 kPa; (b) 100 kPa; (c) 150 kPa.
Figure 7. SEM images of uncontaminated and acid-contaminated soils for (a) pH = 7, 2 μm; (b) pH = 2, 2 μm; (c) pH = 7, 5 μm; (d) pH = 2, 5 μm.

Figure 8 shows the relationship between the overburden stress and direct shear strength under different pH values, along with the cohesion and internal friction angle for each condition. When the soil was exposed to the alkaline solution, the cohesion increased from 2.5 kPa at pH = 7 to 9.1 kPa at pH = 12, while the internal friction angle decreased from 36.5° at pH = 7 to 32.5° at pH = 12, which is consistent with the report of Sunil et al. [63]. For the acid-contaminated soil, the cohesion increased from 2.5 kPa to 11.6 kPa and the internal friction angle decreased from 36.5° to 28° when the pH value decreased from 7 to 5. When the pH value further decreased to 2, the cohesion decreased sharply from 11.6 kPa to 3.3 kPa and the internal friction angle increased from 28° to 33.2°.

Figure 8. Shear strength, cohesion c, and internal friction angle φ of the acid- and alkali-contaminated soils.

3.2. Acid- and Alkali-Contaminated Soils Treated with XG–oat Combination
3.2.1. Moisture Content and Germination Ratio

Figure 9 shows the growth of oats in the acid- and alkali-contaminated soils treated with 0.25% XG at the 7th day of plant cultivation. The trends of the volumetric moisture contents for the soils exposed to the solutions with different pH values were basically the same (Figure 10a). Due to the strong acid dissolution capacity of sulfuric acid [27,57,60], the
acid-contaminated soil became much more porous compared with the other conditions (Figure 7), and therefore the moisture within the soil had more paths to evaporate, resulting in the lowest water content (i.e., pH = 2). However, due to the water retention effect of XG [23,64], the volumetric moisture contents of the soils with different pH values did not diverge remarkably. Figure 10b shows that the germination ratios of oats were the highest (i.e., 95.63%) under the condition of pH = 9, and lowest (i.e., 64.38%) under the condition of pH = 2, respectively. The low germination ratio of oats at pH = 2 may be due to the reduction in the soil fertility caused by the soil organic matter being eroded by the strong acid [27,57,60]. On the other hand, the germination ratio of oats became higher as the pH increased from 7 to 9, and decreased when the alkaline pH value further increased to 12. This phenomenon was also observed in the previous studies. According to [65], the root hairs of oats are promoted under low concentration alkali stress, but inhibited under high concentration alkali stress. Numerous studies have focused on the adverse effect of high soil pH value on plant growth, indicating that the deficiencies in essential elements (i.e., P, Fe and Zn) as a result of reduced solubility [66,67], and NH₄ toxicity resulting from the dissociation of NH₄⁺ at a pH value above 9, will severely inhibit plant germination and growth [66-68]. Overall, the addition of XG helped to improve the soil environment [23] and promoted the growth of oats with the germination ratio above 60% for all the pH values.

![Image](https://example.com/image)

**Figure 9.** Oat growth in the soil treated with 0.25% XG (on the 7th day).

![Image](https://example.com/image)

**Figure 10.** (a) Relationship between volumetric moisture content and cultivation time (0.25% XG content); (b) relationship between germination ratio and cultivation time (0.25% XG content).

Figure 11a further confirms that oats grew better in neutral, weakly acidic, and weakly alkaline soils, and Figure 11b indicates that the volumetric moisture content slightly increased with the increasing pore fluid pH value. In addition, the volumetric moisture contents of the soil were roughly inversely proportional to the germination ratios (Figure 11c–e); that is, the higher the germination ratio of oats, the lower the volumetric moisture content of the soil. This is mainly because the promoted oat growth underwent a higher level of transpiration and consumed more water from the soil through the oat roots [17]. An exception was observed for pH = 2 with both the low germination ratio
and low volumetric moisture content due to the adverse impact of the strong acidic solution on reducing soil fertility [27,57,60] and increasing water evaporation due to the increased porosity (Figure 7).

Figure 11. (a) Germination ratio versus pH value; (b) volumetric moisture content versus pH value; (c) germination ratio and volumetric moisture content versus pH value (0.00% XG-oat); (d) germination ratio and volumetric moisture content versus pH value (0.50% XG-oat); (e) Germination ratio and volumetric moisture content versus pH value (1.00% XG-oat).
Figure 12a indicates that XG could promote oat germination as long as an appropriate XG content was used (e.g., 0.25% XG and 0.50% XG). Mixing an excessive content of XG with soil might end up in a hard XG–soil matrix [24], which would plug the pores for the transportation of water, air, and nutrients (Figure 13) and therefore hinder the growth of oats. On the other hand, the addition of XG increased the volumetric moisture content of the soil, i.e., the volumetric moisture content of the soil generally increased with the XG content at any pH value (Figure 12b). In addition, the increment in the volumetric moisture content was more remarkable as the XG content increased to 0.75% and 1.00%. This is partially due to the inhibited germination and growth of oats at 0.75% XG and 1.00% XG (Figure 12c,d), resulting in less water consumption through plant transpiration. That the higher XG content brought the soil higher water retention capacity might be part of the cause as well [23,64].
Figure 12. (a) Germination ratio versus XG content; (b) volumetric moisture content versus XG content; (c) germination ratio and volumetric moisture content versus XG content (pH = 2); (d) germination ratio and volumetric moisture content versus XG content (pH = 7); (e) germination ratio and volumetric moisture content versus XG content (pH = 12).

Figure 13. Formation of crusts on top and accumulation of water on the soil surface (1.00% XG–oat).

3.2.2. Direct Shear Test

Figure 14 presents the results of the direct shear tests conducted on the acid- and alkali-contaminated soils treated with the XG–oat soil reinforcing method. It is obvious that the combination of XG and oat significantly improved the soil strength, i.e., the soils treated with the XG–oat combination (i.e., represented by the dotted line) had higher shear strength values than the untreated soils (i.e., represented by the solid line) at any pH values. Moreover, the addition of XG improved the shear strength of the vegetated soils, especially for those exposed to acidic solutions. For example, the maximum shear strength values at pH = 2 were 55.8, 98.7, and 125.2 kPa under the overburden stresses of 50, 100, and 150 kPa, respectively, corresponding to the 0.50% XG–oat combination, while the vegetated soil without XG had much lowered strength values of 53.7, 73.6, and 103.9 kPa under the three overburden stresses, respectively (Figure 14a). With the increase in pH values, the positive effect of XG on improving the soil shear strength gradually diminished. For example, at pH = 2, incorporating XG with any concentration (i.e., from 0.25% XG to 1.00% XG) led to a higher strength compared with the case without XG (Figure 14a). When the pH increased to 9 or 12, only the addition of 0.25% XG and 0.50% XG led to a higher strength compared with the case without XG (Figure 14d,e). Overall, for acidic and neutral pH values (i.e., pH = 2, 5 and 7), the direct shear strength of the soil treated with the 0.5% XG–oat combination was the highest, while for the alkaline pH values (i.e., pH = 9 and 12), the 0.25% XG–oat combination was the most efficient in soil strengthening. Excessive XG contents, which hindered the oat growth, were less effective in improving the soil strength, due to insufficient interaction between the soil particles and oat roots.
Figure 14. Shear strength, cohesion $c$, and internal friction angle $\phi$ with increasing XG contents under (a) pH = 2; (b) pH = 5; (c) pH = 7; (d) pH = 9; (e) pH = 12.

Figure 15 shows the values of the cohesion and internal friction angle under different pH values or different XG contents. It was observed that for the three treatment conditions (oat-only, 0.25% XG-oat, and 0.5% XG-oat), the cohesion first decreased and then increased, while the internal friction angle showed an opposite trend with the increasing pH value (Figure 15a,b). When a higher XG content (i.e., 0.75% and 1.00%) was used, the cohesion and internal friction angle did not change with a distinct trend (Figure 15a,b). In addition, the cohesion of the acid- and alkali-contaminated soil first decreased and then...
increased with the increasing XG content, while the internal friction angle showed an opposite trend (Figure 15c,d). However, for the uncontaminated soil, the cohesion first increased and then decreased, and the internal friction angle did not change significantly with the increase in XG content (Figure 15c,d).

Figure 15. (a) Cohesion versus pH value; (b) internal friction angle versus pH value; (c) cohesion versus XG content; (d) internal friction angle versus XG content.

Figure 16a presents the variation in direct shear strength (at overburden stress = 150 kPa) with the increasing XG content under different pH values. Obviously, adding an appropriate amount of XG (i.e., 0.25% XG and 0.50% XG) helped to increase the soil shear strength. Generally, the shear strength of the soil was positively related to the germination ratio, i.e., the higher shear strength was accompanied by the higher germination ratio due to the more sufficient interaction between the oat roots and soil particles (Figure 16b–f). Exceptions were observed in Figure 16c,e, where the 0.50% XG–oat combination led to a smaller germination ratio but a higher shear strength compared with the 0.25% XG–oat combination. This might be because the shear strength of the soil was not only affected by the root mass ratio but by the remaining XG in the soil as well. For the 0.50% XG–oat combination, a smaller germination ratio means that, possibly, less XG was consumed to support oat growth and therefore a larger amount of XG might remain in the soil sample compared with the 0.25% XG–oat combination due to both the lower XG consumption and higher blending content (i.e., 0.50% XG > 0.25% XG). It is possible that the beneficial effect of XG exceeded that of the oat roots and hence the 0.50% XG–oat combination led to a higher shear strength than the 0.25% XG–oat combination (Figure 16c,e).
Figure 16. (a) Direct shear strength versus XG content; (b) direct shear strength and germination ratio versus XG content (pH = 2); (c) direct shear strength and germination ratio versus XG content (pH = 5); (d) direct shear strength and germination ratio versus XG content (pH = 7); (e) direct shear strength and germination ratio versus XG content (pH = 9); (f) direct shear strength and germination ratio versus XG content (pH = 12) for the soils under overburden stress = 150 kPa.
3.2.3. Heavy Metal Element Analysis

Figure 17 shows the XRF analysis of the heavy metal element contents of the untreated soil and the soil treated with the 0.25% XG–oat combination. The XG–oat combination significantly reduced the content and type of the heavy metal elements in the soil. The contents of the some heavy metal elements were reduced by more than 50% (e.g., Zn, Zr, Rb, V, and Cr), and some heavy metal elements were even identified as not existing in the soil (e.g., Pb, Ce, Y, Ag, Co, Nb, and Ga) due to the metal element absorption capacity of plants [69,70]. Therefore, apart from enhancing the soil strength [25], the biopolymer–plant soil reinforcing method is able to improve the soil environment by extracting the heavy metal elements from the soil and therefore preventing the heavy metal elements from flowing out with underground water and polluting other areas. In this context, it is also suggested to use the biopolymer–plant soil reinforcing method for strengthening and remediating the weak soil that also faces the problem of heavy metal pollution.

![Figure 17. XRF analysis of the heavy metal elements of the untreated soil and the soil treated with the 0.25% XG–oat combination (pH = 7).](image)

3.3. Discussion

In this paper, laboratory work to improve the geotechnical performances of acid- and alkali-contaminated clayey soil with the XG–oat combination is presented. Both the plant cultivation tests and direct shear tests were conducted to identify the effect of biopolymer in promoting plant growth in acidic and alkaline soil environments and explore the efficiency of the XG–oat combination in improving the shear strength of the acid- and alkali-contaminated clayey soil. The main observations are as follows:

1. The exposure to acidic and alkaline pollutants changed the Atterberg limits and shear strength of the clayey soil (Figures 5 and 6). The acid-contaminated soil underwent more severe degradation in geotechnical properties compared with the alkali-contaminated soil (Figures 5 and 6).
2. An appropriate amount of XG (e.g., 0.25% and 0.50%) promoted the plant growth and increased the seed germination ratio (Figure 12). Excessive XG content (e.g., 0.75% and 1.00%) may lead to the formation of a hard XG–soil matrix, preventing seed germination and root growth (Figure 12).
3. The shear strength of the vegetated soil was positively related to the seed germination ratio (Figure 16). Both 0.25% XG and 0.50% XG that mostly promoted the plant growth, also led to the higher soil shear strength (Figure 16). In addition, a higher XG content (i.e., 0.50% XG) was demanded in the acid-contaminated soil, while a lower XG content (i.e., 0.25% XG) was demanded in the alkali-contaminated soil (Figures 14 and 16).
4. Apart from enhancing soil strength, the XG–oat combination reduced the types and contents of heavy metal elements in the soil as well (Figure 17).
4. Conclusions

Acidic and alkaline contaminations affect the geotechnical properties of clayey soil. The test results from the current study convincingly reveal the promising performance of biopolymer–plant combinations in reinforcing clayey soils with different pore fluid pH values. Biopolymers with an appropriate blending content are effective in promoting plant growth, leading to the enhanced shear strength of the vegetated soil. The plant roots, due to their heavy metal elements sorption capacity, also contribute to the reduction in the types and contents of the heavy metal elements in the soil. Hence, it is suggested to use biopolymers in combination with plants to improve the geotechnical performances of the acid- and alkali-contaminated soils.

Author Contributions: Conceptualization, J.N. and G.H.; investigation, G.H., J.C. and S.L.; writing—original draft preparation, J.C.; writing—review and editing, J.N., X.G. and J.C.; funding acquisition, J.N. and X.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Natural Science Foundation of China, grant number 51608323, and 51978533; European Union’s Horizon 2020 Framework program Marie Skłodowska-Curie Individual Fellowships, grant number 897701; Marie Skłodowska-Curie Actions Research and Innovation Staff Exchange (RISE), grant number 778360.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The work described in this paper was supported by the National Natural Science Foundation of China (51608323, 51978533). In addition, this project has received funding from the European Union’s Horizon 2020 Framework programme Marie Skłodowska-Curie Individual Fellowships under grant agreement No. 897701 and Marie Skłodowska-Curie Actions Research and Innovation Staff Exchange (RISE) under grant agreement No. 778360.

Conflicts of Interest: The authors declare no conflict of interest.

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