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ORIGINAL PAPER

The short-term and long-term performance of biopolymer-remediated soils

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Abstract
This paper discusses the short- and long-term durability of biopolymer-treated coarse-grained soils. Despite their promise as an environmentally friendly alternative to traditional methods, the durability of biopolymer-treated soils has been a limiting factor in their widespread adoption. Therefore, we consider the durability of biopolymer-treated soils at two different stages after treatment: For short-term durability, the biopolymer gel is present in the pore structure of the soil, improving it through its finite yield stress and viscosity. In this case, our work focuses on assessing the durability against cyclic drying and wetting. The results show that, due to the pore-clogging effect of the biopolymer, rapid moisture variations and the majority of biological degradation are concentrated in a thin outer crust. Long-term durability is studied in terms of the synergistic effects of biopolymer and plant roots on soil shear strength. Biopolymer increased root diameter and, in the early stages, decreased total root length.

Introduction

When mixed with water, water-soluble biopolymers (e.g., Xanthan gum and other polysaccharides) form a viscous gel with a finite yield stress. When they are used for soil treatment, they fundamentally change the properties of the pore fluid from water (a Newtonian fluid) to a viscoelastic gel [1–4]. Therefore, they improve soil properties through a different mechanism compared to the common chemical soil treatment methods that primarily rely on forming cementitious bonds between particles (e.g., lime and cement treatment). In other words, the former method is based on *modifying/engineering the pore fluid*, which has been proposed as an alternative method [5–9] to the traditional cement-based methods that rely on modifying the soil skeleton.

Traditional cement-based soil improvement methods expose humans to health risks from cement dust and degraded groundwater quality; they also negatively affect soil chemistry, which ultimately affects vegetation growth. Finally, the production of traditional soil stabilizers is energy-intensive and contributes to global greenhouse gas emissions [10]. The detrimental health, environmental, and economic costs of the traditional soil stabilizers are the main incentives for the current surge in research into the use of biopolymers to improve the mechanical properties of coarse-grained soils [2–4, 11–13]. However, there are established standard test methods for assessing the durability of cement-based soil treatments (e.g., ASTM D559/D559M-15). Unfortunately, no such standard exists for soils treated with pore fluid engineering methods.

The durability of biopolymer-remediated soil improvement techniques is one of the frequently asked questions about these techniques. Thus, this study focuses on the short-term and long-term durability aspects of biopolymer-treated soils. The short-term durability focuses on the ability of fresh biopolymer treatments to endure harsh environmental conditions while continuing to enhance the desired hydraulic and mechanical soil properties. We specifically focus on cyclic drying and wetting utilizing the standardized techniques generally used to assess the durability of cement-based soil treatments (ASTM D559/D559M-15). We will show that these techniques do not provide a fair assessment of the durability of soils whose pore fluid has been replaced with engineered soft matter, such as fresh biopolymer gels. We will then discuss a few modifications adopted to suit these standardized techniques for pore fluid-modified soils.

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The long-term durability of biopolymer-treated soils will also be discussed. From that perspective, we argue that biopolymers degrade in soil into other compounds due to chemical, biological, and/or solar degradation. Chemical degradation could be due to unintended interactions with the substances existing in the soil that might break down polymer chains. Such degradation can be addressed during the design phase by selecting a biopolymer that is stable against pre-determined chemicals in the ground. The latter two degradations (i.e., biological and solar) are expected to occur in the topsoil, which is the top few centimeters and up to two meters of the ground [14]. Thus, we focus our long-term durability study on this critical zone. We investigate how the presence of degrading biopolymers at these shallow depths can promote other processes that can result in the secondary stabilization of these shallow soil masses. Specifically, we will focus on the impact of biopolymers on grassroots growth and how the combined effect of grassroots and degraded biopolymers affects the shear strength of the treated soil.

In this paper, Xanthan Gum (XG) is used as a model biopolymer to treat coarse-grained soils. Other researchers have also used XG in geotechnical engineering to reduce the hydraulic conductivity of silty sand via pore clogging and as a soil strengthener [4, 15, 16]. Clay fillers (Bentonite and Kaolinite) are also added to XG because of past research showing beneficial synergistic effects on the behavior of biopolymer-treated sandy soil, such as reducing the swelling behavior of the soil [17].

For the short-term durability analysis, compacted XG-treated soil specimens are subjected to drying and wetting cycles according to ASTM D559 standard [18], the progression and mechanism of failure, as well as the seepage of water into the compacted soil specimen, were monitored and studied. Moreover, using a custom-made centrifuge setup, the pore fluid containing the biopolymer was extracted back out of the soil and studied using rheological and Fourier Transform Infrared (FTIR) spectroscopy to identify signs of physical or biological deterioration of the biopolymer.

For the long-term durability assessment, pre-germinated ryegrass seeds were cultivated in compacted XG-treated sandy soil. The roots were washed and scanned after 2, 6, and 10 weeks to obtain root growth parameters. Moreover, soil specimens were obtained with minimal disturbance and tested with a direct shear test setup at the same time intervals to study the combined effects of ryegrass roots and degrading biopolymer in the soil.

Experimental procedure

The materials and sample preparation methods used in this study are explained in more detail elsewhere for the short-term study [16, 19] and for the long-term study [20, 21]. Briefly, the soil used for the drying and wetting experiments was Badger Sand, a poorly graded sand with no fines (SP) ($C_u = 2.83$, $C_c = 1.66$, $G_s = 2.87$, $e_{min} = 0.41$, $e_{max} = 0.75$). For the study on the combined effects of biopolymer and grassroots, a well-graded sand (Acco Sand) was used ($C_u = 9.29$, $C_c = 1.66$, $G_s = 2.87$, $e_{min} = 0.44$, $e_{max} = 0.87$). Other materials used include food-grade Xanthan gum (XG) was bought in powder form; Edgar Plastic Kaolin (EPK) was bought commercially from Edgar Minerals (PL = 32%, LL = 67%) [22]; sodium bentonite with no polymer additives was bought commercially from Baroid Fluid Services (PL = 55%, LL = 420%); and de-ionized (DI) water was used in all experiments to prepare the gels. When the environmental conditions are not explicitly stated for the tests described below, they are ambient room conditions (20 ± 2 °C and ~ 30% relative humidity year-round).

Short-term study sample preparation and testing:

The weight of XG was 0.5%, and 1% of the dry weight of sand and the weight of water was selected as 14% of the dry weight of sand based on the standard Proctor compaction curves (ASTM D698-12 2021). The majority of research performed on biopolymer treatment of coarse-grained soils use biopolymer-to-soil ratios less than 2% [2–4, 11–13]. This is one of the advantages of biopolymers compared to cement, which typically requires 10% cement per unit weight of soil. XG was mixed with the appropriate weight of water first, and the ensuing gel was mixed with the soil using a planetary mixer. When clays were used, the clay was also added to the XG gel before mixing with the soil. The weight of clay fillers was selected as 25% of the XG's dry weight (i.e., 0.125% and 0.25% with respect to the dry weight of soil for the 0.5% and 1% treated soils). The clay filler to XG ratio of 25% was selected based on previous work by Antonette and colleagues that showed beneficial synergistic effects of clays on XG-treated sand, such as reduced swelling behavior [17]. Samples were made using a standard 100 mm (4-inches) compaction mold at maximum dry unit weight using the standard Proctor compaction method described in ASTM 698 method A [23]. At least three specimens were made for each cyclic dry/wet test set.

The cyclic drying and wetting tests were performed according to the ASTM D559/D559M [18]. This standard specifies 7 days of curing period in a humid room (100% humidity) followed by 12 cycles of wetting and drying. In this standard, 5 h of submerging in a water bath was done to simulate wetting, and oven drying at an elevated temperature of 71 ± 3°C (160 ± 5°F) for 42 h was done for the drying step. After each drying step, any spilled sand at the bottom of the pan was removed carefully and the specimen weight was recorded. The use of scratch wire brush was eliminated due to the soft nature of wet biopolymer-treated soil, other researchers also recommended the elimination of this step from ASTM D559 [24, 25].

Figure 1a shows the specimen after the 1st and 3rd wetting cycles. Figure 1b shows the sampling locations inside a compacted soil specimen. The water content of these samples was obtained using oven drying. Moreover, the gel pore fluid was also extracted back out of the soil using the custom-made centrifuge setup, which utilizes a #200 wire mesh suspended in a conical centrifuge tube. The extracted gels were studied using Rheological and FTIR spectroscopy tests.

Rheological measurements were performed on these gels using an Anton Paar MCR302e rheometer using a plate-plate geometry. FTIR study was performed using a Single Reflection Attenuated Total Reflectance FTIR (ATR-FTIR) machine (Thermo-Scientific Model 6700 FTIR spectrometer). A small drop of the extracted gel was placed on the FTIR-ATR crystal. A fan was used to accelerate the drying of the gel droplet on the crystal since drying helps remove the water signal from the spectrum.

Long-term study sample preparation and testing:

For this portion of the study, the well-graded sandy soil was compacted to 70% relative density at the water content

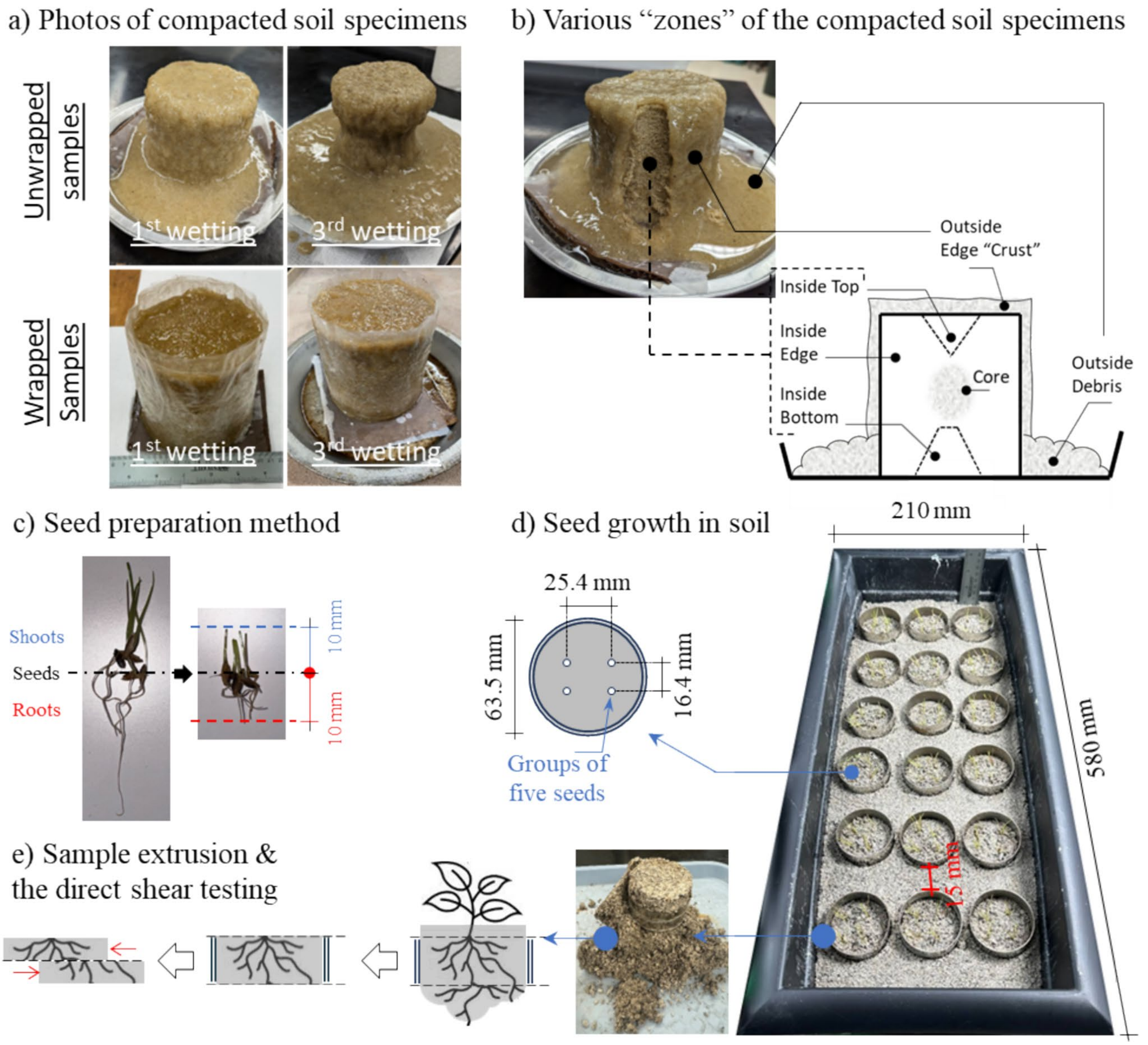

Fig. 1 **a** photos of the soil specimens after the 1st and 3rd rounds of wetting. Both wrapped and unwrapped specimens are featured; **b** a photo and sketch showing different zones of a specimen right after the end of the wetting stage; **c** pre-germinated seeds before and after trimming; **d** cultivation box and seed positions; **e** sample extrusion and direct shear procedure

of 8.3% using the under-compaction method [26]. XG gel was 0% (no biopolymer), 0.5%, and 1.5% relative to the dry weight of the sand. The soil was compacted in five layers in a 220 mm by 580 mm container to a height of 141 mm using a 203.2 mm square tamper. Eighteen direct shear ring samplers (diameter 63.5 mm; height 25.4 mm) were positioned on the soil surface, and the pre-germinated ryegrass seeds were planted in groups of five in the four corners of each ring. Each ring was watered with 6.5 ml of tap water daily, representing average daily rainfall in the United States. Specimens were extracted after 2, 6, and 10 weeks to scan and study the root growth and to prepare specimens for direct shear testing. Details of the root scanning and direct shear tests are presented elsewhere [20, 21]. Since the soil in this section of the study is not experiencing significant moisture content variations, expansive soil behavior was not of concern, and therefore, no clay fillers were used in this section of the study. The steps involved in seed germination, growth, and extraction are shown schematically in Fig. 1c–e.

Results and discussion

Short-term study

As discussed, drying and wetting experiments were performed according to the ASTM D559/D559M standard [18]. In all cases, the weight of the specimen declined with each cycle due to excessive loss of sand after each wetting period. Specimens containing clay fillers showed more rapid weight loss than those prepared using XG only. The specimens treated with 0.5% XG collapsed after the first wetting cycle. Therefore, further tests on these specimens were discontinued. All specimens with 1% XG and XG fortified with Kaolinite failed on the fourth wetting cycle, and the specimens fortified with Bentonite failed on the third wetting cycle.

It was frequently observed that specimens fail due to (a) soil loss in the peripheries of the specimen and (b) soil loss near the specimen midsection. The first failure mode is not likely to occur in the field, where extended soil layers are treated with biopolymers. This is, therefore, one of the shortcomings of applying the current ASTM method to the biopolymer-treated soils. The latter failure mode creates an hourglass shape (the 3rd wetting cycle shown in Fig. 1a). Soils treated with pure XG and the soils treated with XG and Bentonite showed both failure mechanisms, whereas the soils with XG and Kaolinite failed through the first failure mode.

The second failure mode is reminiscent of failure under compressive stress. One potential explanation for this failure mode is that the biopolymer film forming and shrinking during the drying phase applies internal compressive stresses on the soil, resulting in the observed failure mode. No measurements of the internal stresses were made inside the soil specimens. However, as it will be shown next, it was observed that despite cycles of wetting, the internal parts of the specimens continue to lose moisture. This continuous drying of the internal sections may support this potential explanation.

Following each wetting cycle, one soil specimen was dissected to obtain samples from different zones of the soil block (b). Figure 2a–c shows the water content of the different zones. As can be seen, the debris and the wet crust on the specimen have water contents that are an order of magnitude higher than the inner parts of the specimen. There is also a wet core inside the specimen that kept its original water content within the first few cycles of drying (Fig. 2a–c). The water content of the samples taken from the zones between the wet core and the wet crust (“inside” in Fig. 1b) declined after each drying cycle and did not bounce back during the 5-h submersion (wetting) cycles due to the low hydraulic conductivity of the hydrated crust. This contrast of moisture contents can be seen in the photo presented in Fig. 1b also.

As expected, the yield stress of the gels extracted out of the pore structure of different zones followed an inverted trend, with higher water content zones showing lower yield stress (Fig. 2d–f). It is noteworthy that the yield stress of the pore fluid extracted from the crust of all three cases of biopolymer-treated soils is relatively constant across different wetting and drying cycles. This can be explained by the fact that this yield stress (~ 10 Pa) must be the minimum yield stress of the pore fluid that helps sand particles stick to the walls of the cylindrical specimen, while a yield stress below this number results in the sliding of those particles off the walls and into the debris.

Figure 2g–i shows the absorbed CO_2 detected by the FTIR in the gel [27]. A freshly prepared biopolymer gel would show zero absorbed CO_2 bands with the FTIR test (these bands appear in the 2300 cm^{-1} to 2400 cm^{-1} wavelength range). The full FTIR spectra of the freshly prepared biopolymer gels are shown in the supplementary information Figure SI-2. One explanation for the appearance and increase in the absorbed CO_2 could be the enzymatic decomposition of the gel by the soil microorganisms [28]. Figure 2g–i shows that the samples collected from the crust and debris tended to have more adsorbed CO_2 than the inner parts of the soil specimen, probably due to the aerobic nature of the organisms that consume XG. The appearance of the CO_2 bands also occurred in the control specimens that were not subjected to cyclic wetting and drying (data not shown). Therefore, biological degradation is independent of the physical degradation that might occur from wetting and drying.

One criticism of using absorbed CO_2 as a measure of biopolymer degradation is the indirect nature of this measurement. However, biopolymers can be degraded by fungi

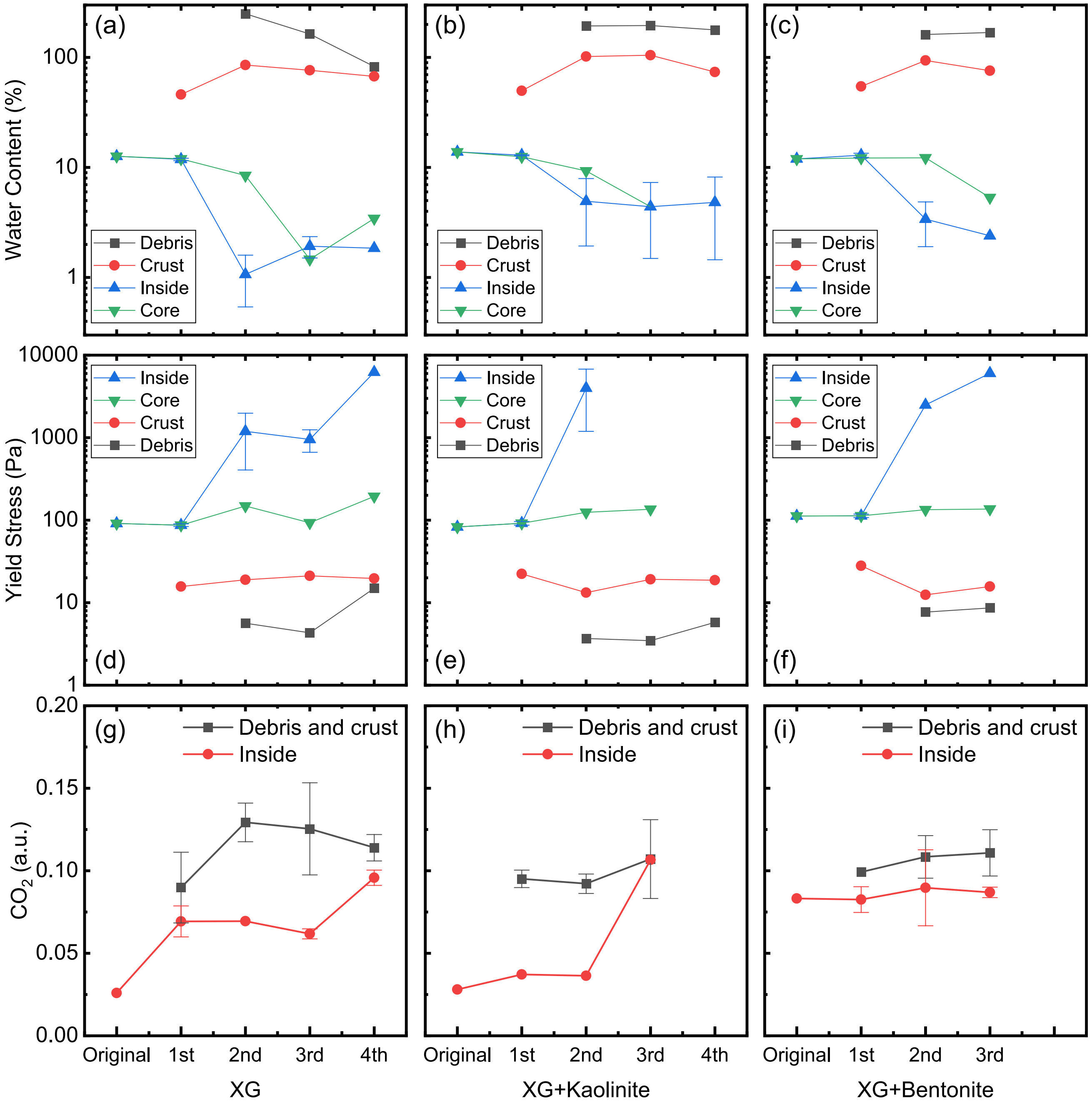

Fig. 2 **a**–**c** The water content of samples collected from different "zones" of the compacted 1% biopolymer-treated specimens. **d**–**f** The yield stress of the extracted gel from the same zones. The magnitude of CO_2 detected by the FTIR in the extracted gel from the same zones. In this figure, "original" refers to the compacted soil specimen after 7 days of curing in the humid room, and the graphs on the left (**a**, **d**, **f**) show results for 1% XG treatment without clay fillers; graphs (**b**, **e**, **h**) show the cases with kaolinite; and (**c**, **f**, **i**) show the cases with bentonite clay fillers

and microbes into carbon dioxide, methane, water, inorganic compounds, or biomass by the enzymatic action of microorganisms [28–30]. A photo showing mold growth on the compacted soil specimens is shown in the supplementary information in Figure SI-3. Tracking individual organisms that feed on Xanthan Gum is outside the scope of this paper. Moreover, the fungal cell wall is composed of chitin and glucans covered by proteins; therefore, its FTIR spectrum overlaps the spectra of XG, other natural polymers, and macromolecules [31]. In our specimens, the mold peak appears at 1650 cm^{-1} (Supplementary

Information Figure SI-4). As a result of these limitations, we opted to measure CO_2 as a by-product of XG degradation.

Excessive mass loss from compacted soil specimens is the main roadblock to using currently available standards for the durability assessment of biopolymer-treated soils. Therefore, a series of tests was conducted with compacted soils wrapped on the sides in heat-resistant plastic. These specimens were treated similarly with cycles of wetting and drying. Figure 1a shows photos of two of these specimens after the first and third cycles of wetting. These modified specimens survived the full 12 cycles of wetting and drying. Although these specimens were not dissected for analysis of different zones, the midsection of the specimen had visibly higher moisture content at every drying cycle up to the 12th cycle (drying and wetting mainly occurred from the top and bottom surfaces).

These specimens were tested using the Unconfined Compression Test (UCT) after the first and after even drying cycles. The variability in the moisture content of the specimens created variability in the UCT results, which are presented in the Supplementary Information section (Figure SI-1). Visual inspection of specimen failure modes under UCT showed that during the first few cycles, samples failed from the soft, wet midsection, squeezing outward. With the progression of wetting and drying cycles, the volume of dry portions increased, and the wet midsection became a wet core inside the specimen. Therefore, the failure mode switched to the wet core, punching out and cracking the dry shell. This switch in the failure mode occurred after the 6th drying cycle. A noticeable increase in the peak UCT stress is observed from the 4th to the 6th cycle without much increase afterward.

Long-term study

To study the long-term repercussions of biopolymer treatment, Ryegrass seeds were pre-germinated for 7 days in groups of five seeds on wet paper towels. This minimized root entanglement to ensure root development could be assumed independent for each group. Figure 1c and d presents photos of the pre-germinated seeds, the cultivation box, and a sketch of the seed locations in each direct shear sampling ring. The sampling rings helped extract samples with minimum disturbance for the direct shear tests (Fig. 1e).

Scanning and image processing of the extracted roots were used to measure the total root length and diameter, as shown in Fig. 3a and b. Root weight (Fig. 3c) was measured after air-drying the roots. As can be seen, the total length of the roots increases in all cases with time, and after 10 weeks, there is no statistically significant difference between the three cases. However, the 1.5% XG initially (2 weeks) had shorter root lengths than the other two cases studied. The average root diameter for the 1.5% XG was statistically larger throughout the experiment.

These results show that although a high concentration of XG (1.5%) in the short term inhibits root length growth compared to clean sand, these plants experience a more rapid root growth rate in longer periods. This can also be seen in Fig. 3d, where the root length normalized by root weight (root length density) is presented. In the case of clean sand, the RDL decreases from 2 to 6 weeks and remains constant from 6 to 10 weeks. The decrease in root length density from weeks 2 to 6 is also seen in the case of both XG-treated soils. However, from weeks 6 to 10, these roots experienced an increase in density. This could be due to the degradation of the biopolymer in the soil into nutrients for these roots, although more research is needed to confirm this statement.

The shear stress versus deformation of clean sand with and without roots is presented in Fig. 4a. Each case is tested on two to three independent specimens, and the solid line shows the average of the tests. The stress-deformation behavior of the clean sand with no roots almost overlaps with the early (2-week-old roots) stage. The 6- and 10-week roots seem to overlap up to 8 mm of deformation with the previous curves before the strengthening effects of the roots take effect. A similar behavior was observed in the stress-deformation curves of the 0.5% and 1.5% XG-treated soils (Fig. 4b and c). The specimens with and without roots overlap initially, and the presence of roots resulted in higher shear stresses only at higher deformations. This observation suggests that in both root and no-root cases, the initial resistance is provided by the soil network alone and that the presence of roots only affects stress-deformation response at higher deformations.

Comparing the 2-week curves (the red curves across Fig. 4a–c) shows that the samples treated with 0.5% and 1.5% XG exhibited two and three times higher maximum shear stress values, respectively, compared to untreated samples. Tests performed on biopolymer-treated soil alone (i.e., no roots) showed a modest increase in the maximum shear resistance. Therefore, adding biopolymers enhances root–soil interaction, contributing to improved soil reinforcement during the early stages of root development.

After 6 and 10 weeks, the shear stress remained highest for the 1.5% XG-treated samples, demonstrating sustained soil reinforcement benefits and continued root growth. The 0.5% XG-treated samples also outperformed the untreated samples, indicating improved root anchorage and soil strength over time. In the case of the 1.5% XG, the presence of roots seems to increase the sample's initial stiffness and switch the soil's behavior from the bilinear behavior seen in the 0.5% to a behavior showing peak stress followed by strain softening.

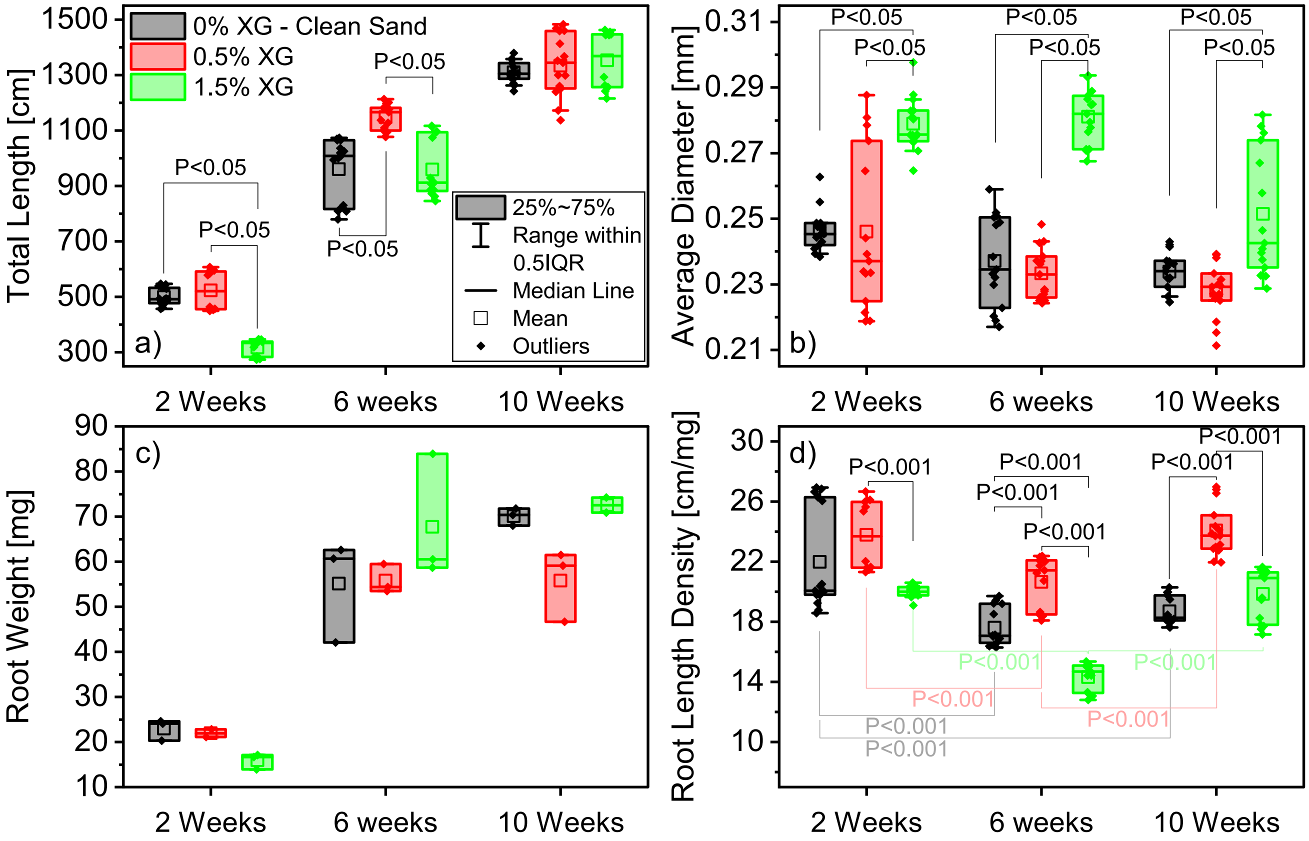

Fig. 3 **a** Total root length; **b** average root diameter; **c** root weight; **d** root length density (RDL)

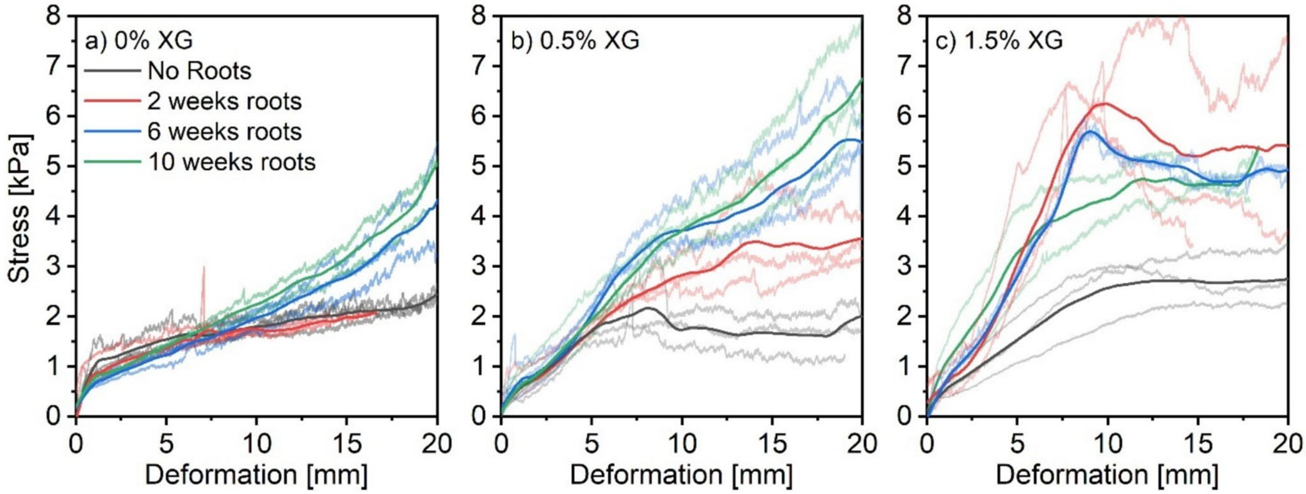

Fig. 4 Stress-deformation plots with and without roots from the modified direct shear test. **a** For clean sand; and **b** for 0.5% XG. The 6- and 10-week results in 1.5% XG samples (graph **c**) were affected by sample disturbance

Conclusion

This paper investigated both the short- and long-term durability of biopolymer-treated soils by focusing on XG as a model biopolymer, cyclic drying and wetting as the short-term environmental damage, and ryegrass seed growth as a method of offsetting long-term degradation of the biopolymer in the soil. Care must be taken when extending the results of this paper to other types of biopolymers and other plant roots, because other biopolymers might affect the short-term durability and root growth in significantly different ways (see, for example [32]). Moreover, it must be noted that the biopolymer gel in this study was prepared in a sterile environment; the tools used during sample preparation (e.g., compaction mold, proctor hammer, etc.) were also disinfected before use. However, the soil was deliberately not sterilized. Therefore, the biological degradation of the biopolymer occurs due to the natural organisms present in the soil. The rate of biological degradation of biopolymers in other soils might vary depending on the initial amount and type of microorganisms present.

Compacted soil specimens were dissected after cycles of wetting and drying to discover the progression and mechanism of failure, as well as the seepage of water into the compacted soil specimen. This allowed concurrent study of both physical degradation of biopolymer (due to drying and wetting) as well as biological degradation (due to the enzymatic action of organisms in the soil). Furthermore, this study analyzed the impact of biopolymer on root growth and the combined effect of biopolymer and roots on the shear strength of surficial soil. The growth of roots and the shear strength of soil were assessed in untreated sand, and sand treated with 0.5% and 1.5% xanthan gum over 2-, 6-, and 10-week periods. The following conclusions are drawn based on these tests:

- The short-term integrity of the compacted biopolymer-treated soil specimens was heavily affected by the formation of an impervious crust during the wetting cycles. This thin (~ 8 mm) layer absorbed water and prevented further seeping of the water inside the specimen. The higher water content (i.e., lower yield stress) of this layer, on the other hand, results in excessive soil loss and premature specimen failure.
- This material loss from the sides of the specimen after each cycle of wetting is not representative of the field behavior of biopolymer-treated soils. Therefore, wrapping the compacted soil specimen could be a potential modification to the available ASTM D559 standard for biopolymer-treated soils.
- The rheological properties of the biopolymer-engineered pore fluid strongly depend on its water content. Therefore, special attention must be given to the specimen's water content and any potential inhomogeneity in the distribution of moisture inside the specimen prior to mechanical testing of the treated soil.
- The extracted pore gels showed signs of biological degradation as detected by the FTIR analysis.
- Since the biological degradation seems to be more severe on the outside surface of the soil specimens, the use of a sacrificial layer in the field may provide degradation control for the biopolymer-treated soils.
- The addition of XG to the soil changed normal root growth by increasing root diameter and decreasing total root length in the early development stages of the plant. These differences eroded with continued plant growth. Roots in the XG-treaded soils showed higher root length density by the 10-week mark.
- Biopolymers and roots synergistically enhance the shear strength of the soil with the roots mostly influencing soil shear strength only at larger deformations.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1557/s43580-025-01432-3.

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Author contributions Mohammadhasan Sasar: conceptualization, visualization, methodology, investigation, and writing—original draft preparation; Sherif L Abdelaziz: conceptualization, supervision, and writing—reviewing and editing.

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Data availability The authors declare that the data supporting the findings of this study are available within the paper and is available upon request.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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