28th European Young Geotechnical Engineers Conference – EYGEC 2024
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Water retention characteristics and drained shear strength of soil treated with newly developed soil conditioners

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ABSTRACT

The impact of climate change has become increasingly severe also in forests, where droughts and strong winds on one, and extreme rainfall events on the other hand can damage forest ecosystems. To mitigate the effects of drought and to increase the soil water retention capacity, various soil conditioners (SCs) are being developed. The laboratory investigation focused on the influence of Xanthan-gum (XG) based SCs with different cellulose fillers on forest soil properties. The primary emphasis was placed on assessing the impact of SCs on water retention ability and hydraulic conductivity. Additionally, a part of the research was directed towards evaluating the drained shear strength of SCs treated forest soil, which is crucial for assessing slope stability, particularly when SCs are used in thick layers on larger, steeper slopes.

This paper deals with the results of laboratory investigations carried out on untreated and treated forest soil, sampled on the ONEforest project case study site in the Alpine part of Slovenia, Ljubelj. The results show significant increase in water absorption of treated soil and favourable impact of SCs on the soil water retention curve (SWRC) in the suction range of plant available water. The increase depends on the amount and type of the SC. A less favourable impact of SCs on drained shear strength was found. The drained shear strength of treated and saturated forest soil was lower than drained shear strength of untreated soil. The decrease in drained shear strength also depends on the amount and type of used SC.

KEYWORDS

Forest Soil; Soil Conditioner; Drained shear strength; Soil hydraulic properties

1. INTRODUCTION

Reports on extreme climatic events over the world, such as droughts and floods, are becoming more and more frequent. Changing environmental conditions require novel solutions to mitigate the negative effects of such extreme events also in the forest ecosystems. Soil conditioners are one of the attempts to elevate soil properties, e.g., enhancing soil's physical, mechanical, chemical and biological attributes. An important aspect is also the retention of water in time of its abundance and regulating its release when plants and trees are in need (Thakur et al., 2023).

Development of commercial SCs is based on implementing highly absorbent hydrogels from organic or inorganic sources (El-Saied et al., 2004; Thakur et al., 2023). The application of synthetic, inorganic soil conditioners is limited by high cost and can represent negative effect on environment (El-Saied et al., 2004; Cabalar et al., 2018; Kwon et al., 2019; Lee et al., 2023b; Sorze et al., 2023b). Organic polymers, on the other hand, offer a sustainable alternative for soil treatment and can foster soil microorganisms and enhance soil structure (Thakur et al., 2023). Cellulosic material, for example, is known for its high absorption properties (El-Saied et al., 2004; Pan and Ragauskas, 2012; Sorze et al., 2023b) and is easily accessible. Hydrogels made of organic material are reported to retain up to 100 % more water than untreated soil even after 5th day of irrigation (Yangyuoru et al., 2009). A significant increase in water retention properties of soil treated by hydrogel made from lignocellulosic waste was reported by (El-Saied et al., 2004).

Another example of organic polymer is Xanthan Gum (XG), which is a natural polysaccharide produced by fermentation process that increases material's viscosity and shear stability even at low concentrations (Tran et al., 2018; Cabalar et al., 2018; Kwon et al., 2019). Addition of XG into the soil has been extensively reported in the literature in recent years exhibiting promising results. Due to a significant reduction in its market price has become one of the most investigated biopolymers in geotechnical engineering (Mendonça et al., 2020; Oliveira and Reis, 2023). Compared to other biopolymers, XG demonstrates superior improvements of soil in terms of strength properties, erosion resistance and reduction of hydraulic conductivity along with increased vegetation (Tran et al., 2018; Cabalar et al., 2018; Kwon et al., 2019; Soldo and Miletić, 2019; Lee et al., 2023b).

However, promising results of XG treated soils in partially saturated state are accompanied by the fact that XG is extremely sensitive to presence of water, which transforms high strength polymeric network to a weak gel-like material (Chen et al., 2020; Lee et al., 2023a), inherently affecting the soil strength and stability.

Within European project ONEforest, new types of SCs were developed Cellulose fillers were added to the XG to enhance and optimize the performance of XG in terms of hydraulic properties and structural stability (Sorze et al., 2023a, 2023b). The main objective of our research was the assessment of the influence of newly developed SCs on the soil properties with the focus on the length of cellulose fillers in the SCs. Investigations were performed on mixtures of Slovenian forest soil and three types of SCs. The influence of the SCs type and the dosage of SCs on drained shear strength of treated soil was assessed. Using falling head permeameter, saturated hydraulic conductivity was measured. Comparison between water absorption capacity of untreated soil and mixtures was made. Water retention characteristics were determined for untreated soil and mixtures over a wide suction range.

2. MATERIALS AND METHODS

For the research, the forest soil from Ljubelj area in the Alpine region of Slovenia was used, which was one of the case study sites within ONEforest project (CESEFOR, 2021). A soil sample was taken from a layer beneath the fresh organic layer, approximately 10 cm below the surface. Despite the depth of sampling, the soil sample contained a minimal amount of partially decomposed organic matter. All visible undegraded organic material, such as leaves and needles, was removed before laboratory investigations. Sample of Ljubelj soil at natural water content is shown in Figure 1 (left picture).

Three types of SCs were used for the investigation, i.e., Arbocell R (SC_R), Cellugrün (SC_CG) and ZZC500 (SC_ZZC). All are based on XG with different types and amounts of fillers with diverse fibre lengths. SC_R has the highest cellulose content (>99 %) and shortest fibres (200-300 μm), while SC_CG and SC_ZZC has the same cellulose content (80 %) and fibres with length of 1400 μm and 400 μm, respectively. The appearance of the SCs is shown in Figure 1 in dry (left half of the picture) and wet state (right half of the picture). It is evident that the addition of water extremely alters the texture of SCs resulting in hydrogel-like paste with significantly increased volume due to swelling.

More information about the SCs and their development can be found in (Sorze et al., 2023a, 2023b).

Laboratory tests were performed on untreated soil and mixtures of soil and SCs according to the test program as shown in Table 1, where list of executed investigations and corresponding standards and methods are reported. In mixtures, the soil conditioner SC_R was used in low (L) and high (H) dosage with 0.4 % and 1.7 % of SC per dry soil weight, respectively, while soil conditioners SC_CG and SC_ZZC were used only in high (H) dosage of 1.7 %.

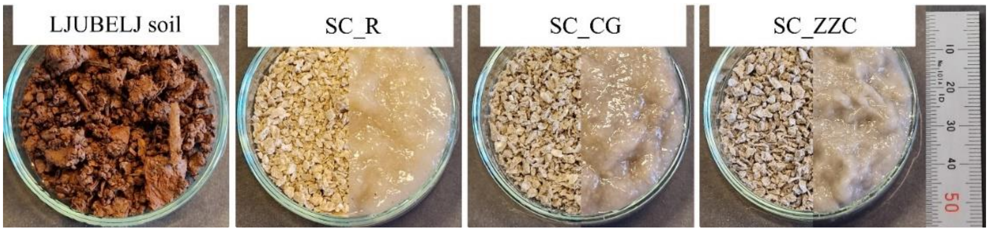

Figure 1. Sample of Ljubelj soil (picture on the left) and three types of soil conditioners in dry and wet state (three pictures on the right)

Table 1. Laboratory investigations, associated standard and investigation plan

Parameter	Standard/Method	Soil	Mixtures
(gravimetric) water content	EN ISO 17892-1 / T_{drying} = 45°C	✓	✓
sieving analysis	EN ISO 17892-4	✓	×
particle density	EN ISO 17892-3	✓	×
water absorption	DIN 18132 / Enslin-Neff – 1.0 g	✓	✓
shear strength – direct shear test	EN ISO 17892-10 / 60-60-20 mm	✓	✓
liquid limit, plastic limit	EN ISO 17892-12	✓	×
soil suction (SWRC)	ASTM D6836, manufacturer's instructions	✓	✓
hydraulic conductivity	EN ISO 17892-11 / falling head	✓	✓

Prior to measurements of water absorption, the soil was dried until constant mass. Dry soil and SCs were separately grinded and sieved through 0.355 mm sieve and then mixed together. 1.0 g of specimen were used for Enslin-Neff absorption test. For other tests, the mixtures were prepared by mixing the soil at natural water content and dry soil conditioners.

For the direct shear (DS) test, the specimens of soil and mixtures were compacted into the mold at dry density of approx. 1.5 g/cm^3. To achieve full saturation of the specimen, the assembly was submerged under water before consolidation stage. For the mixtures, the swelling took place for at least 24 hours. Afterwards, the specimens were consolidated gradually until final effective vertical stresses (50 kPa, 100 kPa and 150 kPa) were achieved. The specimens remained submerged also during shearing stage. Shearing rate was set at 0.002 mm/min. To prove the repeatability of the DS test, two repetitions were carried out for mixtures with the addition of SC_R H and SC_ZZC H.

Specimens for measurements of saturated hydraulic conductivity in oedometer cell, were prepared in a similar manner, with swelling stage at the beginning of the test with 4.5 kPa of vertical load. Hydraulic conductivity *k* was measured at the end of consolidation process at two vertical loading stages, i.e., 25 kPa and 50 kPa.

Water retention curves for soil and mixtures (SWRC) were determined using two devices:

- Hyprop was used for measurements of matric suction below approx. 100 kPa with evaporation method (Peters and Durner, 2008). The specimens of soil and mixtures were assembled into the sampling ring with diameter and height of 8 cm and 5 cm, respectively, at density of approx. 1.5 g/cm^3. Specimens were immersed in water to their 4/5 height until saturation higher than 90 % was achieved. Due to considerable swelling, vertical deformations were reduced by porous discs on upper and lower surface of the specimen and with the 10 kPa weight on top of the specimen during saturation process. After saturation, two Hyprop tensiometers were installed in pre-drilled boreholes within the specimen. Prepared specimen was placed on a balance and measurements were started. To ensure quasi constant hydraulic conditions within the sample, water evaporation rate was slowed down by covering specimens with perforated plastic bag. It was assumed that decrease in mass of the specimen corresponds to the amount of evaporated water thus potential degradation during the investigation, which lasted at least 1 month, wasn't considered.
- Dew point potentiometer WP4-T was used for suctions higher than 100 kPa. (WP4 Operator's manual, 2003; Maček et al., 2013). For the sample preparation, the water was gradually added

to the mixtures, so the sample was wetted near full saturation state. Approximately 5 g of the mixture was placed into dedicated plastic container for suction measurements of the specimen in saturated state. Remaining mixture was gradually air dried until required water content was reached. Before each measurement, the containers were airtight sealed for at least 24 h in order to provide uniform water content distribution throughout the specimens.

The dry mass of all specimens was determined after suction measurements by drying in an oven at 45 °C.

3. RESULTS

3.1. Index properties of soil

Natural water content w_0, liquid limit w_L and plasticity index I_P of the Ljubelj soil was 43 %, 67 % and 26 %, respectively and particle density was 2.52 g/cm^3. Investigated soil was fine grained and contains 83 % fines (< 0.063 mm), while the maximum particle diameter was 8 mm. According to the USCS classification the Ljubelj soil was classified as elastic silt with sand.

3.2. Water absorption

While the water absorption tests on untreated soil were finished within 1 h, the addition of the SCs into the soil resulted in prolongation of the tests. The tests on mixtures were carried out for at least 48 h to ensure that full capacity of the SCs was exploited. For each specimen 2 to 4 test repetitions were performed and average values were considered. In Figure 2, the water absorption capacities after 24 h ($w_{A,24\,h}$) and maximal water absorption capacities ($w_{A,max}$) are shown. The addition of high dosage of SCs notably increased water absorption capacity of Ljubelj soil. After 24 h, the highest impact had the SC_R H, while the overall highest increase in water absorption was achieved by mixture with SC_CG. The dosage of the SCs played an important role in increasing water absorption capacity of the soil, as can be seen from Figure 2, while the impact of the SC type was not as considerable.

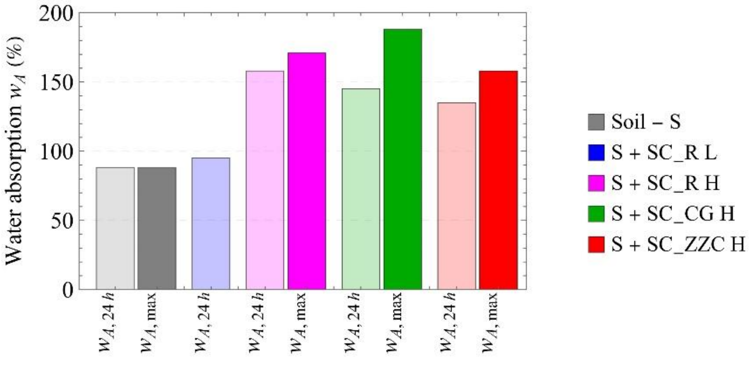

Figure 2. Water absorption capacity for Ljubelj soil and mixtures

3.3. Drained shear strength

The results of direct shear tests carried out on saturated untreated soil and mixtures are shown in Table 2. In order to exclude the influence of inhomogeneities in the prepared mixtures, the tests of S+SC_R H and S+SC_ZZC H were performed with two independent replicates, labelled 1 and 2 in Table 2. The obtained results demonstrate satisfactory repeatability in the direct shear tests.

The addition of SCs generally reduced the drained shear strength of saturated specimens. The friction angle φ' was lower for all mixtures compared to the untreated soil. With a low dosage of SC_R, the decrease in the friction angle was slightly lower than with a high dosage of SC_R. Among the mixtures with a high dosage of SC, the highest friction angle was achieved by SC with the longest fibre length, i.e., SC_CG, which also had the lowest effective cohesion c’. Interestingly, the low dosage of SC_R resulted in a considerably higher cohesion compared to untreated soil and mixtures with high dosage of SC.

Table 2. The results of direct shear tests: effective cohesion c’ and effective friction angle φ’ of the untreated soil and of the mixtures in saturated state

Specimen	c’ (kPa)	φ’ (°)
Untreated soil – S	4.4	33.5
S + SC_R L	11.0	27.0
S + SC_R H – 1	4.0	26.0
S + SC_R H – 2	7.7	25.0
S + SC_CG H	1.6	26.5
S+SC_ZZC H – 1	4.7	24.0
S+SC_ZZC H – 2	5.9	24.0

3.4. Saturated hydraulic conductivity

For each specimen, at least 2 replicates were performed at each loading stage. As the results of the first and subsequent measurements were similar, the average values of the hydraulic conductivity, $k_{10^\circ\mathrm{C}}$, are shown in Figure 3 together with the corresponding void ratio. It is evident that SCs reduce the hydraulic conductivity and that the influence of a low dosage of SC_R was considerably lower compared to a high dosage of SC_R.

Among the mixtures with high dosage, the specimens with SC_CG show the highest values of $k_{10^\circ\mathrm{C}}$ at comparable void ratios. This could be an indication of the influence of the filler properties. The results also show that the hydraulic conductivity of soil and mixtures depends on the void ratio as expected.

In the literature, similar findings were reported, indicating that the addition of 1 % of XG reduced hydraulic conductivity from $1.42*10^{-7}$ m/s for untreated soil to $4.46*10^{-10}$ m/s for treated silty clay (Anandha Kumar and Sujatha, 2022). The decrease in hydraulic conductivity can be attributed to the inherent rheology modification tendency of XG hydrogels. They elevate the viscosity of the soil pore water and obstruct capillary spaces due to their high viscosity. Consequently, this impedes the free movement of water within the soil pore space (Singh and Das, 2020).

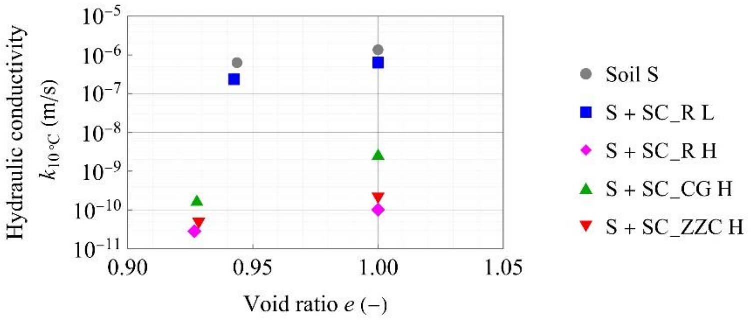

Figure 3. Hydraulic conductivity of untreated soil and mixtures

3.5. Soil water retention curve (SWRC)

Figure 4 shows SWRCs of the untreated soil and mixtures measured by Hyprop (solid line) and WP4-T (scatter plots). The highest (initial) water content of the mixtures was higher than of untreated soil and in the case of SC_R rises with increasing dosage. The lowest measured suctions were between 0.6 kPa (soil) and 9 kPa (S + SC_R H) and reflect initial saturation of specimens. The presence of SCs leads to pore clogging in soils treated with XG-based SCs. This resulted in a prolonged equilibrium time required for the saturation of specimens prior to the tests. Due to difficulties in the saturation process of specimens from mixtures, tests were started when at least 90 % (in most cases 95 %) of initial saturation was achieved. In comparison to untreated soil, specimens from mixtures with a high dosage of SC (1.7 %) exhibit an initial water content that is 16 % to 34 % higher. These findings align with those reported by (Wang et al., 2023; Zhang et al., 2023). (Wang et al., 2023) observed a 1.3-fold increase in initial water content for silty soil treated with 1% XG, while (Zhang et al., 2023) noted a 1.2-fold increase for sandy soil treated with 2% XG.

SWRCs indicate that, at high suction (> 2000 kPa), there was no notable difference in the water retention capacity between mixtures and untreated soil. In the low suction range (< 100 kPa), the water retention capacity of mixtures was higher than that of the untreated soil. In the medium suction range (100 kPa – 2000 kPa), the scatter of the results was similar for mixtures and soil. The observed scatter could be a consequence of WP4-T device accuracy, which is declared to be ± 10 kPa for the suctions below 1000 kPa and/or reflect the influence of SCs. Higher efficacy of XG in low suction ranges has been confirmed also by previous studies. (Wang et al., 2023) found out that the improvement in water retention of silty soil was the highest in the suctions up to 100 kPa, while at suctions higher than 10000 kPa, the effect of XG was negligible.

The observed differences in the position of SWRCs of mixtures in the range of suction up to 100 kPa indicate the influence of the SC type. The SWRCs of the mixtures with high dosage of SC_R and SC_ZZC are the highest, while the mixture with high dosage of SC_CG is close to the SWRC of the mixture with low dosage of SC_R. As shown in Figure 4, two independent investigations were performed to determine the SWRC for the mixture with SC_R H, which is depicted in detail within the black rectangle in Figure 4. Although the mixtures were prepared in two replicates and tests were performed with different tensiometers and Hyprop devices, the results are in good agreement.

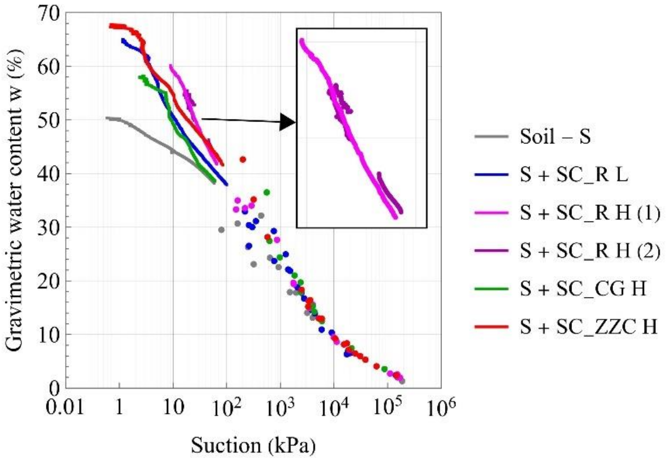

Figure 4. SWRC for untreated soil and mixtures

4. CONCLUSIONS

The study investigated the influence of newly developed XG based SCs on the drained shear strength and hydraulic properties of forest soil from the Alpine region of Slovenia. The SCs differ from each other in the properties of the fillers within the XG matrix.

The study acknowledged the importance of the type of SC, especially in relation to the length of the cellulose fibers. The main conclusions can be summarized as follows:

- In saturated conditions, the effective cohesion and friction angle of mixtures decreased compared to untreated soil, except for the low dosage of SC_R, whose mixture had higher effective cohesion than untreated soil. Among the high dosage mixtures, SC_CG with the longest fibers showed the highest effective friction angle. It has been shown that dosage of the SCs is more important than type of the SC.

- The addition of a high dosage of SCs strongly increased the water absorption capacity compared to untreated soil. The low dosage mixture had a comparable water absorption capacity to untreated soil.
- Due to the gel-like texture of the SCs in wet state, their addition to the soil resulted in a decrease in saturated hydraulic conductivity. The decrease was greater in mixtures with high dosage of SC_R than with low dosage. The mixture with SC_CG exhibited in the highest hydraulic conductivity among the high dosage mixtures.
- The water retention ability was notably increased by the addition of all types of SCs in the range of low suctions (< 100 kPa). The increase depends on the amount of SC added. In the case of a high dosage of SCs, the SWRC of the mixture with SC_CG H was lower than the SWRC of the other high dosage mixtures.

The results confirmed the influence of SC dosage on the drained shear strength and the hydraulic properties of the soils. The impact of SC_CG slightly differed from SC_R and SC_ZZC at the same dosages, indicating the importance of cellulose fiber length.
The authenticity of the results was confirmed by a repeatability check for all investigations. However, it should be noted, that the type of soil treated may also be a crucial factor in validating the influence of SC on drained shear strength and hydraulic properties.

ACKNOWLEDGEMENTS

The authors acknowledge the funding provided by the European Union's Horizon 2020 Research and Innovation Program within the project ONEForest: A Multi-Criteria Decision Support System for A Common Forest Management to Strengthen Forest Resilience, Harmonise Stakeholder Interests and Ensure Sustainable Wood Flows (Grant Agreement No 101000406).

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The paper was published in the proceedings of the 28th European Young Geotechnical Engineers Conference and was edited by Elena Angelova. The conference was held from June 25th to June 29th 2024 in Demir Kapija, North Macedonia.