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A study on the durability of xanthan gum strengthened sandy loam

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ABSTRACT

There is a strong push for decarbonisation in the civil engineering industry, as such, environmentally friendly construction materials, such as biopolymers for soil reinforcement, have been studied extensively in geotechnical engineering recently. Biopolymers can offer comparable soil mechanical reinforcement outcomes compared with traditional ground improvement materials, e.g. lime and cement. However, as they are environmentally friendly, biopolymers are also more degradable with the potential of showing a loss of soil reinforcement mechanical functions over time. This paper carried out more in-depth investigations to understand the durability of biopolymer-reinforced soils under different climate conditions. UCS tests, fatigue tests, SEM under wetting and drying cycles and fungal contamination conditions were performed. The results revealed that the UCS value for soil treated with xanthan gum shows a better resistance against wetting and drying cycles than natural soil. However, the treated soil under cyclic loading results in a gradual decrease in fatigue life due to biodegradation and loss of biopolymer. UCS tests results for fungal-contaminated samples indicate that, in the first two weeks, the xanthan gum strengthening effect works normally and shows an increase in UCS compared to the untreated soil. However, starting from the third week, the degradation caused by fungal contamination starts to surpass the biopolymer strengthening effect and leads to a reduction in UCS values. Consequently, additional xanthan gum content in soil samples increases the durability of the treated soil. However, the effect caused by potential fungal contamination under abnormal weather changes needs to be taken into consideration in construction practices.

Keywords: climate change, ground improvement, xanthan gum, compressive strength, fatigue test, fungal contamination

1 INTRODUCTION

Climate change has become one of the biggest challenges for our planet. To better protect our homes, humanity and our natural environment, decarbonisation in the civil engineering industry has been highlighted by our nations. Traditional soil improvements methods such as using lime, fly ash, or cement are widely adopted (Kajaste et al., 2016; Li et al., 2018; Zaman, 2019; Baldovino et al., 2021; Shen et al., 2021). However, these methods caused environmental concerns such as increasing CO2 emission and groundwater contamination (Choi et al., 2020; Rai et al., 2020; Zhang et al., 2020) Therefore, the need for the development of green ground improvement techniques and materials has increased in recent years.

The use of biopolymers in ground improvement has been studied extensively as biopolymers are environmentally friendly materials that do not generate any contamination and influence the local ecosystem. Biopolymers are polymers derived from natural materials of living organisms such as plants and microorganisms (Appelqvist and Debet, 1997). Biopolymers absorb water when mixed with moist soils and form hydrogels, which can enhance inter-particle bonding and therefore increase soil compression and shear strength (Chang et al., 2016; Ni et al., 2020). Existing studies also indicate a significant decrease in soil permeability for biopolymer-treated soils due to the pore-clogging effect (Muguda et al., 2017; Chang et al., 2019; Singh et al., 2020). Previous studies mainly focused on the short-term performance of biopolymer-treated soils. However, biopolymer as a biodegradable material, the biodeterioration caused by the microbial activity can lead to changes in the treated soil's biochemical, physical, and mechanical properties (Gaylarde et al., 2003; Johansson et al., 2012, Vydehi and Moghal,

2022). Therefore, it is essential to understand in more detail on the long-term durability performance of the biopolymer-treated soil.
In this study, xanthan gum is chosen to be the soil binder due to its appropriate strengthening performance and relatively low cost (Chang et al. 2015). To investigate the climate impact on biopolymer-treated soils, UCS and fatigue tests after wetting and drying cycles were conducted and a group of fungi-contaminated samples were studied. SEM was performed to investigate the microstructure of the treated soils before and after the wetting and drying cycles.

2 MATERIALS

2.1 Soil

The soil collected from the top layer of a local site at the University of Warwick was used in this study. The soil was sieved twice through a 1200-micron sieve to eliminate the large aggregates and root residues. The soil particle size distribution curve and Atterberg's limit are given in Fig. 1 and Table 1. The clay, silt, and sand contents are 4.32%, 31.28%, and 64.4%, respectively. Based on BS EN ISO 17892-4 standards, the testing soils are defined as sandy loam.

Table 1. *Soil properties*

Properties	Values
Specific gravity, G_s	2.62
Density of soil, kg/m^3	1752.4
Unit weight of soil, kN/m^3	17.5
Liquid limit, w_L %	29
Water content, %	20
Initial void ratio, %	0.69
Plastic Limit, w_p %	16
Plastic Index, %	13

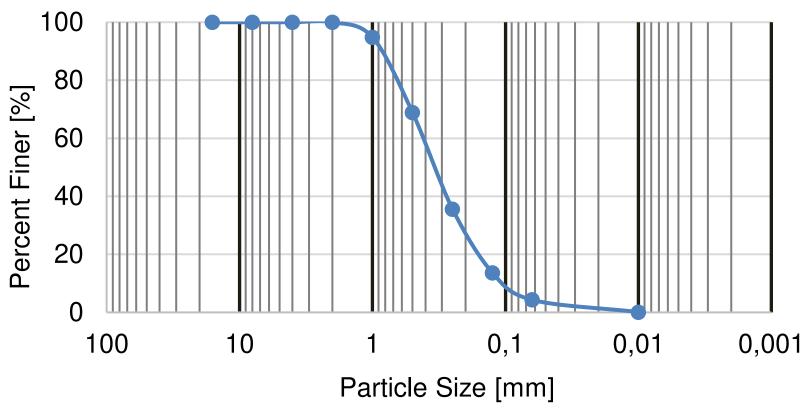

Figure 1. *Particle size distribution curve of the natural soil*

2.2 Biopolymer

Xanthan gum is an anionic polysaccharide commonly used as a food additive and thickener (García-Ochoa et al. 2000); it is produced by the Xanthomonas campestris bacterium. Xanthan gum extra fine powder (produced by Special Ingredients) was used in this study.

3 METHODS

3.1 Sample preparation

A dry mixing method was adopted in this study in order to get an uniform distributed biopolymer powder-soil mixture. The xanthan gum powder was first mixed with oven-dried soil (0% for untreated soil samples and 1.5% for biopolymer treated soil samples). Then the required amount of distilled water based on the optimum water content of the soil was added. A cylindrical mould with an inside diameter of 38 mm and a height of 76 mm was adopted to make the testing samples. According to BS1377-4 standards, each sample was compacted in three layers with each layer applied 30 blows by a rammer (317.5 g). Then the soil samples were sealed in cling film for 24 hrs to reach an equilibrium state. To investigate the biodegradation of xanthan gum treated soil, two separate groups of soil samples were prepared. For the first group of soil samples, fungicide Captan was added (0.2%) to restrain the fungi growth, and for the second group without. The samples for fungal contamination analysis were put in a container under a constant room temperature and a humidity of 100% to simulate a foggy weather environment for a period of 28 days.

3.2 Wetting and drying cycles

The soil samples were first put in a sealed plastic box and dried at room temperature around 20.8 ± 0.3 °C. After the first drying process, the samples were rewetted using a humidifier to reach 100% humidity within the box. The humidifier was chosen to simulate rainy weather conditions, as moist maritime weather is one of the most common weather conditions in the UK. The wetting and drying test was conducted with a total of 3.5 wetting drying cycles, and a time interval of 5 days for each wetting and drying cycle with a total duration of 35 days. The experiment procedure is illustrated in Fig. 2. The concentration of xanthan gum was kept at 1.5% for the experimental groups which was previously identified as the optimum biopolymer content (Chang et al., 2015). The control groups (0% xanthan gum) follow the same wetting and drying procedure as the experimental groups.

To investigate the effect of wetting and drying cycles on the soil samples, both static (UCS) and dynamic (fatigue) tests were conducted, and the water content of each sample was measured after each cycle.

3.2.1 Unconfined Compressive Test

For the soil static performance, UCS tests were performed by utilising a Universal Testing Machine (UTM) Instron 5583. The compression rate was set at 2% (1.5 mm/min) according to the Standard BS EN ISO 17892-7. The maximum axial strain was set at 20% of the sample height (76 mm). For each UCS test, three samples were compressed. After testing, the mean compression strengths for each group of samples were calculated to minimise errors.

3.2.2 Fatigue test

Fatigue test is a particularised form of mechanical testing applying cyclic loading to soil samples, which has been used to investigate the durability of soils. In this study, the same UTM (Instron 5583) was used for performing the fatigue tests. Identical soil samples as the unconfined compression test were utilised. The tests are load controlled. The mean stress (σ_m) and stress amplitude (σ_a) remained constant during fatigue tests. The maximum and minimum loads were derived at 80% and 50% of the mean compression strength according to BS EN 13894-2. The loading frequency was 1 Hz, and the maximum number of loading cycles was set at 100,000 cycles.

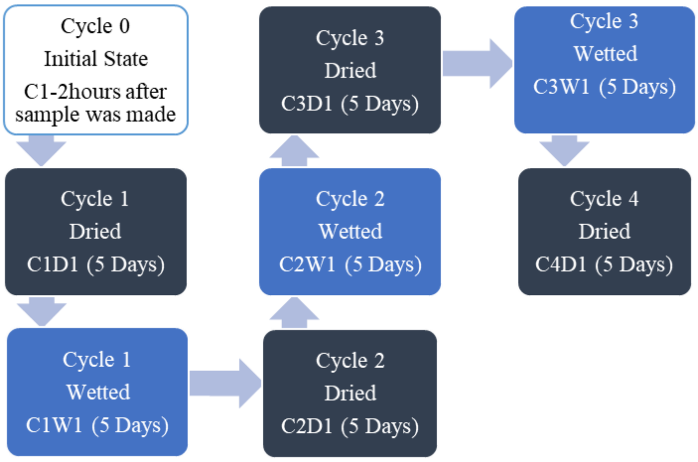

Figure 2. *Wetting and drying cycles testing sample list*

3.3 Fungi contamination analysis

Saprotrophic soil fungi are the most efficient decomposers of biopolymers in the natural environment (Kjoller and Struwe 2002; Baldrian 2008a). Therefore, biopolymer treated soils are at risk of losing strength over time due to fungal activities, especially under a high humidity weather condition which can lead to rapid fungi growth (Pasanen et al., 2000). Fungal contamination can be obvious as it shows coloured stains and patches on the soil surfaces due to mould growth (Brischke and Thelandersson, 2014; So et al., 2016). In that case, fungi can lead to the weathering and degradation of the biopolymer treated samples physically and chemically. Berthelin 1988 stated that fungi can cause the weakening of the mineral matrix by releasing organic acids. In this study, the biodegradation of biopolymer treated soil caused by fungi growth was evaluated by the change in mechanical properties (UCS tests). The UCS tests were conducted at a curing time of 7, 14, 21, and 28 days.

3.4 Microscopic Observation (SEM Images)

To study the microstructure and the interactions between biopolymers and soil particles, SEM (Scanning electron microscope) images were taken before and after the wetting and drying cycles.

4 RESULTS AND DISCUSSION

4.1 Wetting and drying test

4.1.1 UCS test

The static loading performance of soil samples through wetting and drying cycles was investigated using the UCS tests. As it is seen in Fig. 3, the wetting and drying cycles have a marginal impact on dried soil strength for untreated soil samples. Whereas an obvious change in the compressive strengths between the dried and wetted samples was observed. It shows an average of 95% reduction in compression strength. A decrease in compressive strength can be attributed to the change in water content through the wetting and drying cycle (8% for dried samples and 19% for wetted samples). The results indicated that the foggy weather has a significant effect on the untreated sandy loam UCS values, but the compressive strength increased back to its original value upon drying.

As for 1.5% xanthan gum treated soil samples, significantly higher (85% to 174% increase) UCS values were observed compared to the untreated soil samples in both dried and wetted states due to the extra hydrogel formation between the soil particles (Soldo et al., 2020). In addition, a continuous increase in UCS of the treated samples was observed in the first three cycles from 3.3 MPa to 4.7 MPa, after that, it shows a reduction in UCS for the later cycles. This can be attributed to the water absorption characteristics of the xanthan gum. At the initial water content before the wetting and drying test, the water was not enough to make xanthan gum powder fully transfer to the hydrogel state. Thus, the biopolymer further absorbs water in the first three wetting cycles and reaches the optimum state at the third cycle (reaches the maximum UCS value). The reductions in UCS for the rest cycles can be explained as the decrease in xanthan gum concentration and biodegradation of xanthan gum due to the wetting and drying cycles. Previous researchers also reported a reduction in compression strength after wetting and drying cycles (Chang et al., 2017).

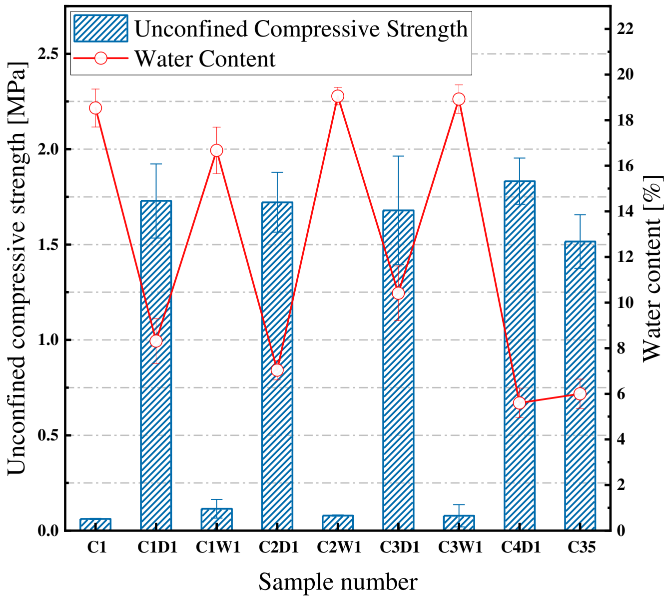

***Figure 3**. The compression strength and water content of untreated samples with cyclic wetting and drying of a 5-day interval*

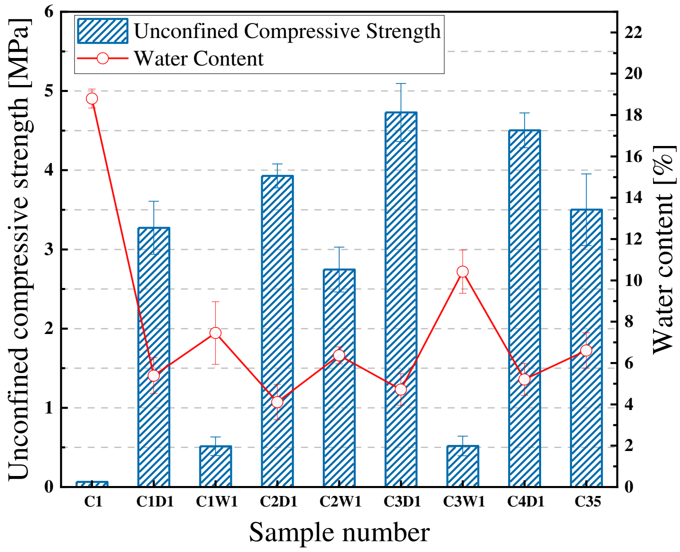

***Figure 4.** The compression stress and water content of xanthan gum (1.5%) treated samples with cyclic wetting and drying of a 5-day interval*

4.1.2 Fatigue tests

Fig 6. presents the results of fatigue tests. At the wetting stage, the wetting and drying cycles show little effect on fatigue life. However, a gradual decrease in fatigue life under the wetting stage was observed for xanthan gum treated soil samples and shows a lower fatigue life compared to the untreated soil samples from the second cycle. This indicates that xanthan gum content in the soil is gradually losing its strengthening effects due to the loss of xanthan gum content and biodegradation of the biopolymer. Whereas, for the dried samples, all the xanthan gum treated samples reached the maximum designed number of cycles (100,000). The results show consistency with other literature that biopolymers show optimum strengthening performance in the dried state. Through the drying of hydrogel structures, the plasticity of the treated soil increases, as a result, it enables the treated soil to resist extra load improving its stiffness and strength (Muguda et al., 2017; Sujatha and Saisree 2019, Chang et al., 2016). Whereas the fatigue life for the untreated soil samples starts to decrease at the third cycle, dropping from 100,000 cycles to 73,714 cycles. This can be attributed to the soil loss due to the wet-dry cycles.

Results from the UCS and fatigue tests under wetting and drying cycles revealed a common phenomenon. The xanthan gum content increases the durability of xanthan gum treated soil under both wetted and dried state for static loading and dried state for dynamic loading.

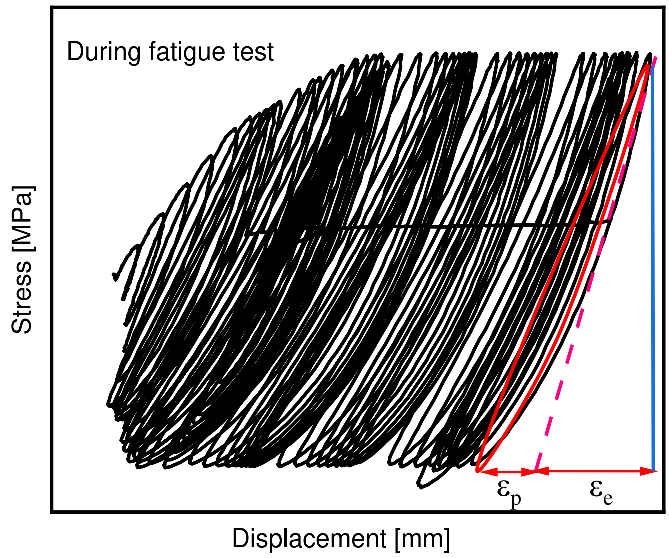

Figure 5. *An example of hysteresis loop during fatigue test*

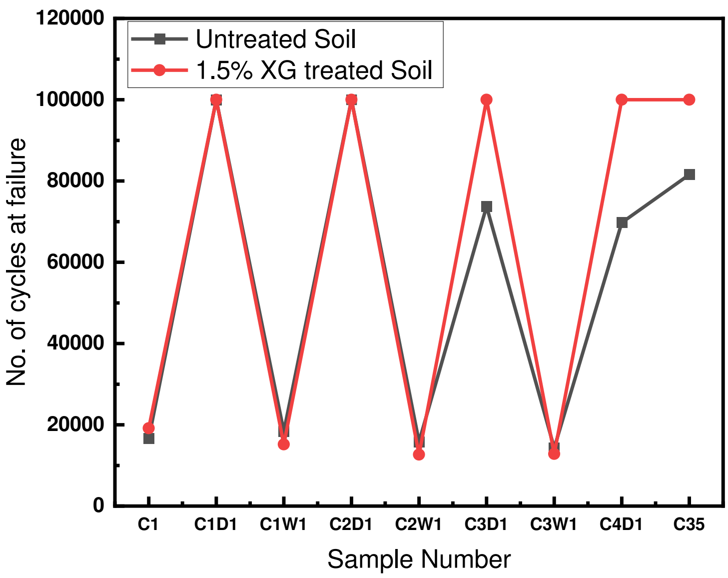

Figure 6. *No. of cycles at failure for each sample*

4.2 SEM Scans

SEM (Scanning Electron Microscope) images were utilised to investigate the microscale interactions between soil particles and xanthan gum. SEM scans for soil samples before and after the wetting and drying cycles are presented in Fig. 7. As shown in Fig. 7a and 7c, there are several gaps between soil particles indicating weak bonding forces between particles and therefore leading to lower UCS for untreated soils. Whereas before the wetting and drying cycles, the image for xanthan gum treated soil

(Fig. 7b) shows clear hydrogel connections between soil particles. After the wet-dry cycles (Fig. 7d), the hydrogel bonds seem shorter and less obvious compared with the samples before the wetting and drying cycles. This reflected the conclusions drawn from the compression tests and fatigue tests that xanthan gum loses its strengthening effect as wetting and drying cycles increase.

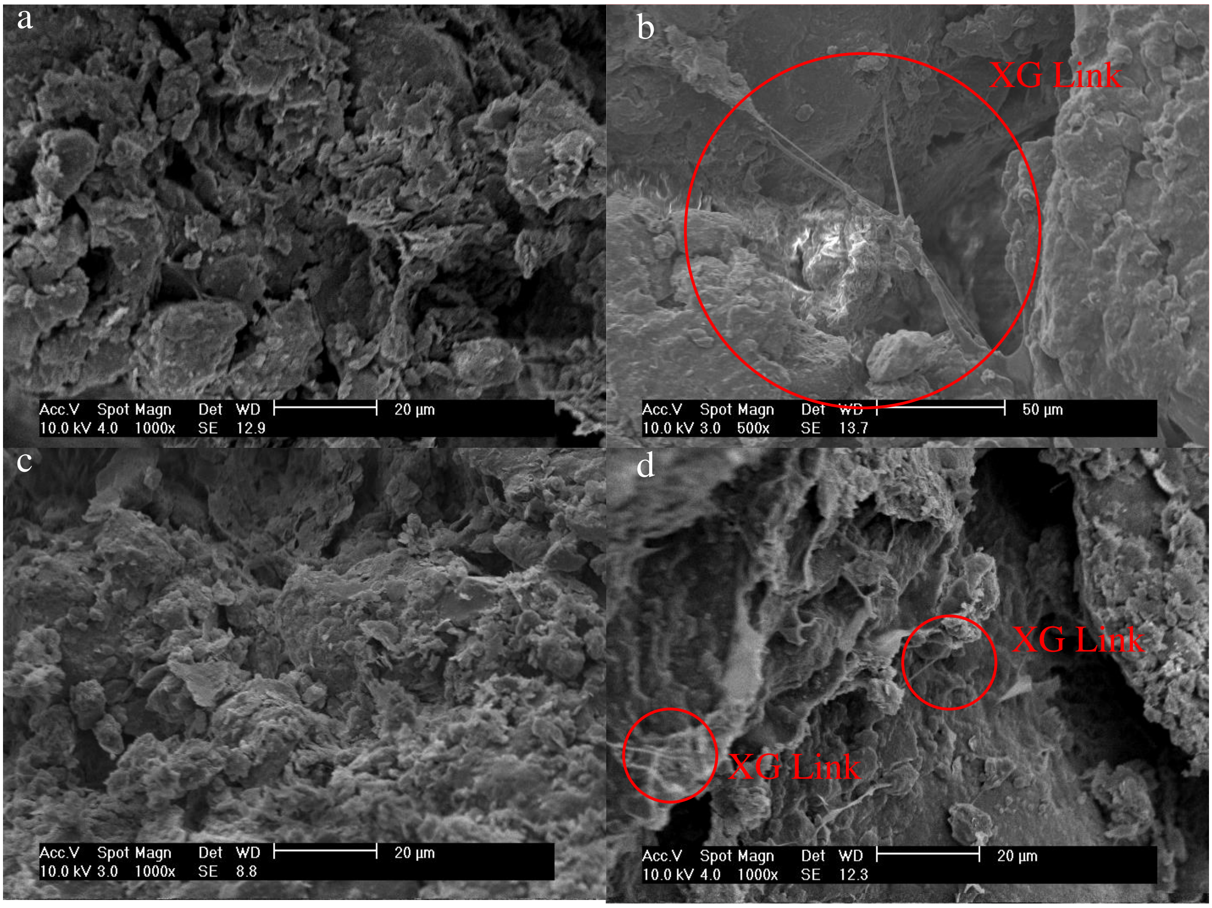

***Figure 7**. SEM Scans **a** Untreated soil sample before wetting and drying cycles **b** 1.5% XG treated soil sample before wetting and drying cycles **c** Untreated soil sample after wetting and drying cycles **d** 1.5% XG treated soil sample after wetting and drying cycles*

4.3 Effect of xanthan gum content under fungi contamination

The UCS tests were conducted on the fungal-contaminated, xanthan gum treated soil samples to reveal the loss in mechanical strength caused by biodegradation on treated soil samples due to fungi contamination. As presented in Fig. 8, the xanthan gum treated soil samples with fungal contamination at different curing times had only little effects or even a drop in UCS value. In the first two weeks, the UCS value shows an increasing trend from 1.43 MPa to 1.91 MPa. After that, the compressive strength value decreases gradually for the rest two weeks. The increase in strength can be caused by further water absorption and biopolymer hydrogel formation due to the high-humidity environment. In the first two weeks, the fungi growth was still at a very early stage, therefore, the effect caused by the degradation of the gum content is still minor compared to the biopolymer strengthening effect. Then for the last two weeks, the degradation caused by fungal contamination starts to surpass the biopolymer strengthening effect and leads to the reduction in UCS values.

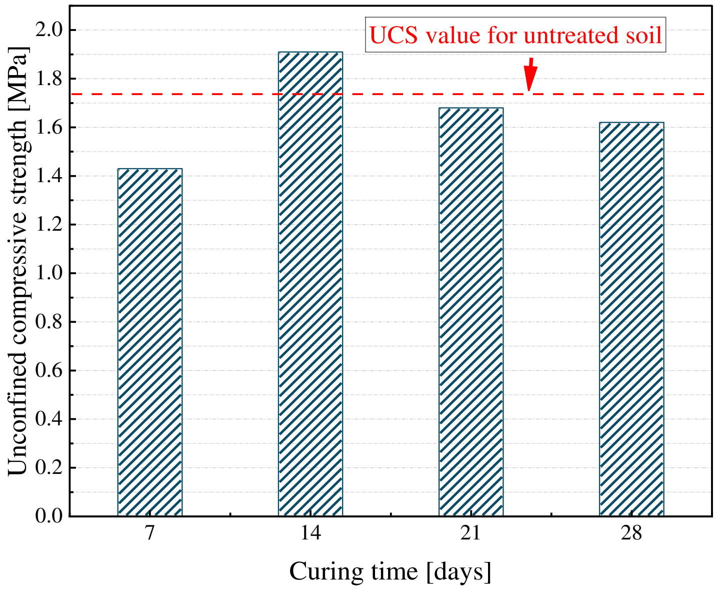

Figure 8. *UCS results for fungal-contaminated xanthan gum treated soil samples under different curing times*

5 CONCLUSION

This paper provides a study on the durability of xanthan gum treated soils from different perspectives. A series of tests were performed on xanthan gum treated sandy loam samples. The results revealed that the simulated foggy weather conditions (wet-dry cycles) can impact on the soil strength regardless with or without xanthan gum treatment. However, with the addition of xanthan gum content, under the static loading, the UCS results showed an 85% - 174% increase in the first three cycles, compared to the soil without the reinforcement. Moreover, for dynamic loading tests, xanthan gum treatment extends the fatigue life of sandy loam during the drying stage. However, the high-humidity environment speeds up the biodegradation process of the gum content in the soil. As a result, xanthan gum treated soils show a gradual decrease in fatigue life at the wetting stage. Moreover, the UCS results for the fungal-contaminated sample indicate a decrease in UCS values after two weeks of curing time. Such loss in strength can also be observed from the SEM images. The hydrogel bonds and coatings were clearly reduced after the wet-dry cycles.

Based on the current results, it can be concluded that xanthan gum improves the mechanical behaviours and durability of soils under climate change (wetting and drying cycles). But it is also suggested to consider the potential fungal contamination when implementing the biopolymer technique in ground improvement practices.

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