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Biopolymer-stabilised soils: Impact on water retention, plasticity, and sorption properties

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Abstract: Due to the growing interest in sustainable and environmentally friendly construction materials, biopolymers are increasingly being explored and applied for soil stabilisation in geotechnical engineering. In this study, particular attention is given to assessing the effectiveness of three widely used biopolymers – xanthan gum, chitosan, and carboxymethylcellulose – added at concentrations of 1, 2, and 3% by soil weight for stabilising the structure and improving the physical properties of heavy sandy clay loam. An additional objective of the research is to examine how varying levels of water saturation influence the performance and stability of these biopolymer-treated soils. A series of laboratory experiments was carried out, including measurements of soil plasticity, natural water content, and consistency limits. Furthermore, sorption behaviour and equilibrium moisture content were determined using the vapour equilibrium technique with saturated sodium chloride and potassium chloride solutions, allowing for controlled regulation of relative humidity. The findings demonstrate that incorporating biopolymers leads to noticeable improvements in Atterberg limits, particularly the plasticity and liquid limits, indicating enhanced cohesion and structural integrity. At the same time, changes in moisture retention characteristics were found to depend strongly on environmental conditions, especially humidity levels and the specific salt solution used. Overall, the results provide valuable insights for predicting soil behaviour under diverse climatic conditions and offer a scientific basis for developing practical recommendations for the use of biopolymers in construction. The study ultimately confirms that such additives represent effective, sustainable, and eco-friendly solutions for improving soil performance in engineering applications.

Keywords: biopolymer, moisture retention, plasticity, sorption characteristics

INTRODUCTION

Modern trends in the construction industry are oriented towards finding environmentally friendly and sustainable solutions, which stimulate the use of natural components and materials. One such solution is biopolymers application, which can improve the construction materials due to their unique properties (Sulaiman *et al.*, 2022). In recent years, scientists and engineers have attracted attention to biopolymers due to their ability to effectively strengthen soil by increasing its mechanical properties and stabilising its structure (Ayeldeen *et al.*, 2017; Seo *et al.*, 2021). All these factors make biopolymers advisable for applications in construction and land management (Tran, Chang and Cho, 2019).

The effect of xanthan gum (weight ratio to the test material 1.5%) and jute fibre (weight ratio to the test material 0.6% with a fibre length of 20 mm) on the hardening of soil dredged from the Yellow River (China) at different degrees of compaction (90, 94 and 98%) was studied by Feng *et al.* (2023). Jute is a long, soft, lustrous natural fibre obtained mainly from the stem and skin of the jute plant. Due to multiple sources of supply, jute fibre is second only to cotton in production and use, mainly in the textile industry. A series of laboratory experiments was conducted to investigate the effect of xanthan gum and jute fibre on the soil mechanical properties. The results showed an improvement in the mechanical properties of the silty sand. Additionally, the microstructure analysis proved that the degree of compaction affects the pore structure of the samples, especially the large pores. Feng *et al.* (2023) revealed that the compaction degree of 94% is an optimal choice for practical engineering applications of silty sand with xanthan gum and jute fibre.

Cheng and Geng (2023) studied the mechanical properties of clay treated with six different biopolymers (xanthan gum, sodium alginate, carrageenan kappa gum, locust bean gum, agar gum and gellan gum), considering different hydration conditions, biopolymer concentration, curing time, wetting-drying time, combination of two different types of biopolymers and method of mixing the biopolymer with soil. The results showed that of the six different biopolymers, the clay treated with sodium algane provided the greatest unconfined compressive strength (from 3.58 to 4.50 times greater than the untreated clay) under the same conditions. Moreover, it was found that the best strengthening was at concentrations of this biopolymer in the range of 1–2% (per 100 g of clay) and curing times ranging from 28 to 42 days. In addition, although biopolymers are environmentally friendly materials with great potential in the biodegradation process, the results of the study showed that the clay treated with xanthan gum could keep compressive strength without limitation even after curing for 378 days and three wetting-drying cycles.

Furthermore, the study of soil sorption properties changes, when adding biopolymers, is revealed to be of key importance for a wide range of engineering and environmental tasks. Soil sorption properties directly affect soil behaviour when the moisture content changes. Mechanical properties of soil with high sorption capacity can be modified depending on the soil moisture level, as biopolymers affect the soil shear strength responsible for its bearing capacity. It is significant for building foundations, where soil stable structure is crucial in preventing deformation and collapse (Tran, Chang and Cho, 2019).

In addition, knowledge of sorption characteristics allows for a more accurate prediction of soil behaviour under different climatic and operational conditions, as well as optimises the choice of construction materials (Rimbarngaye, Mwero and Ronoh 2021). It is essential for the design of earth structures such as dams, roads, and aerodromes, as well as for soil improvement using biopolymers or other additives. For example, Fatehi *et al.* (2024) presented a study of the properties of clayey soils used to construct new railway tracks. As a result, it was revealed that clayey soils generally have high plasticity, their optimum moisture content correlates with the moisture content at the yield strength, and the void ratio decreases with the increasing density of dry samples.

Teh, Wong and Lee (2023) studied the effect of fine particle content on soil moisture behaviour under repeated wetting and drying cycles. Thus, the impact of soil moisture content on soil properties, such as the porosity and the plastic limits, was studied. Tests were conducted on residual soil samples formed at various levels of fines content: 15, 30, 45, 60 and 75%. The soils were fitted with sensors to measure moisture content and subjected to two wetting and drying cycles. All soil samples showed a faster decrease in moisture content during the second drying cycle compared to the first. The effect of moisture migration in the form of geofluids on lateritic soil morphology was investigated in laboratory tests (Onyelowe and Obianyo, 2021).

In contrast, Chang *et al.* (2015b) reported a gradual reduction in the strength of biopolymer-treated soils under repeated wet–dry cycles, although partial recovery was observed after drying. Regarding biodegradation, research by Rimbarngaye, Mwero and Ronoh (2022) indicated that degradation rates depend on polymer type, environmental exposure, and microbial activity.

Current research shows that the application of biopolymers, such as xanthan gum, guar gum and modified celluloses, can significantly affect the sorption properties of soils, enhancing their ability to retain water, cations and pollutants by forming a gel-like structure and increasing the contact area with the aqueous phase (Chang *et al.*, 2015a). Thus, the study of the sorption properties of soils is an essential and multifaceted aspect in engineering, environment, and construction, as it contributes to more sustainable and safer solutions for earth resource management and durability of structures (Sujatha and Saisree, 2019).

This study aims to investigate the effects of carboxymethylcellulose (CMC), xanthan gum (XG), and chitosan (CH) on cohesive soils' physical properties and their structure. In particular, the individual effects of each biopolymer in concentrations of 1, 2 and 3% on heavy sandy clay loam were studied, which represents a significant novelty to the current state of knowledge and practical significance of this study.

STUDY MATERIALS AND METHODS

STUDY MATERIALS

Soil from Astana (Kazakhstan) was used for the experiment. A sieve and an areometer analysis and liquid and plastic limit tests were performed to classify the soil. The sieve and areometer analyses were done following the GOST 12536-2014 (Mezhgosudarstvennyy sovet po standartizatsii, metrologii i sertifikatsii, 2014). The specific density of soil was evaluated according to the GOST 5180-2015 (Mezhgosudarstvennyy sovet po standartizatsii, metrologii i sertifikatsii, 2015). The optimum water content was found according to the GOST 22733-2016 (Mezhgosudarstvennyy sovet po standartizatsii, metrologii i sertifikatsii, 2016) using the standard compaction method, which involves compaction of soils with different water content with the same number of impacts when a weight of 2500 g is dropped from a height of 0.3 m. The physical characteristic of the unmodified soil (US) is presented in Table 1. The US is presented in Photo 1a. According to the GOST 25100-2020 (Mezhgosudarstvennyy sovet po standartizatsii, metrologii i sertifikatsii, 2020), the US was heavy sandy clay loam.

The carboxymethylcellulose (CMC), xanthan gum (XG) and chitosan (CH) were used as soil stabilisers. CMC (Photo 1b) is a cellulose derivative with good water-binding properties (Zhang and Liu, 2023). It can also increase solution viscosity (Muguda *et al.*, 2020), but to a lesser extent than XG (Seo *et al.*, 2021). In practice, CMC stabilises the soil structure and improves its plasticity (Ayeldeen *et al.*, 2017). CH (Photo 1c) is a polysacchar-

Table 1. Physical characteristics of the soil

Soil characteristic	Units	Value
Gravel fraction (>2 mm)	%	5
Sand fraction (1–2 mm)	%	8
Sand fraction (0.24–1 mm)	%	22
Sand fraction (0.1–0.24 mm)	%	25
Sand fraction (0.05-0.1 mm)	%	17
Silty and clay fraction (<0.05 mm)	%	23
Specific density	$kg \cdot m^{-3}$	2.671
Maximum dry density	$kg \cdot m^{-3}$	1.547
Optimum water content	%	9.605
Liquid limit, W_L	%	19.357
Plastic limit, W_P	%	3.170
Plasticity index, I_p	–	16.187

Source: own elaboration.

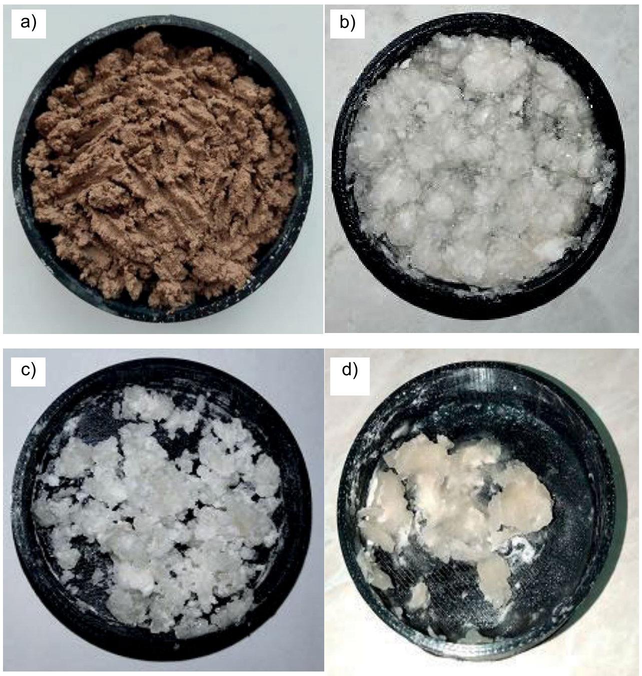

Photo 1. Soil and biopolymers: a) unmodified soil (US); b) carboxymethylcellulose (CMC) 3%; c) chitosan (CH) 2%; d) xanthan gum (XG) 1% (phot.: *Zh. Kusbergenova*)

ide derived from chitin with strong antimicrobial and stabilising properties (Biju and Arnepalli, 2020). CH can form films and gels and modify the soil structure to increase its retention capacity and reduce its permeability to water (Tasuji *et al.*, 2024). XG (Photo 1d) is a highly viscous polysaccharide that can form gels at low concentrations (Bang *et al.*, 2024). XG improves texture and increases soil moisture retention (Ayeldeen *et al.*, 2017).

TESTING PROCEDURES

The studies were conducted in the ENU-Lab of L.N. Gumilyov Eurasian National University, Republic of Kazakhstan. The technical process of the experiment consisted of the following main procedures:

1) determination of physical properties of the unmodified soil (US);
2) preparation of modified soil (CMC, XG, CH);
3) scanning electron microscope (SEM) of US and CMC, XG and CH-modified soils;
4) determination of the US and modified soils' liquid and plastic limits and moisture content;
5) the vapour equilibrium test with the measurement of water absorption (US, CMC, XG and CH).

The impact of 1, 2 and 3% biopolymer concentration on soil properties was tested. The chosen concentration range of biopolymers corresponds to the optimal values that showed an effect on soil that is reported in the literature, i.e. for XG it is ~2%, for CMC ~1–2% (Ayaldeen *et al.*, 2017; Cheng and Geng, 2023), for gelar gum 1–2%, XG ≥ 2 % (Soldo, Miletić and Auad, 2020).

MODIFIED SOIL PREPARATION

Before adding the stabiliser, the US (Photo 1a) was pre-dried in a desiccator at a temperature of about 105°C to a constant mass to exclude the effect of natural moisture on the results of the study (Ayeldeen, Negm and El Sawwaf, 2016). Each type of biopolymer (CMC, XG, CH) was prepared in concentrations of 1, 2 and 3% of the weight of the pre-dried soil sample (300 g). For this purpose, 3, 6, and 9 g of biopolymer were weighed and dissolved in distilled water. Then, the obtained volume of solution was mixed with 300 g of soil. Firstly, modified soil was thoroughly mixed by hand for at least 10 min, followed by mechanical mixing using a planetary mixer for 5 min at medium speed. It ensured uniform distribution of the biopolymer and avoided localised concentrations (Chang *et al.*, 2020). The resulting mass was then stabilised for 1 h to form a more stable and stronger bond between the soil particles (Cheng and Geng, 2023).

SCANNING ELECTRON MICROSCOPE EXAMINATION OF THE SOIL STRUCTURE

A comprehensive microstructural evaluation of CMC, XG and CH-modified soil samples was done using scanning electron microscope (SEM). A scanning electron microscope (TM4000Plus) manufactured by the Japanese company HITACHI was used for observations. To study the mixture structure, the samples of soils modified by biopolymers were dried in the air at 25°C for 10 days, i.e. under conditions that maintain a stable texture and consistency (Lee *et al.*, 2023). After that, the specimen was placed in a high-vacuum microscope chamber and tested.

LIQUID AND PLASTIC LIMITS TEST

The liquid and plastic limits were tested following the GOST 5180-2015 (Mezhgosudarstvennyy sovet po standartizatsii, metrologii i sertifikatsii, 2015). The samples were placed in a porcelain mortar and moistened with distilled water to the state of a thick paste, stirring with a spatula, and then the obtained mixtures were kept in a closed glass vessel for 2 h. After that, the soils were placed in a cylindrical cup on the balance cone, and then the cone was gently lowered to immerse into the paste under its own weight (Photo 2a). Upon reaching the liquid limit, samples weighing 15–20 g were taken from the paste by the requirements stipulated for determining the natural moisture content of the soil. After 2, 4 and 6 days of curing, the liquid limit was also tested to assess the dynamics of liquid limit changes in time for modified soils. In total, 37 liquid limit tests were conducted.

The plastic limit was determined as the moisture content of the paste prepared from the tested soil at which the paste, rolled into a bundle with a diameter of 3 mm, begins disintegrating into pieces with a length of 3–10 mm (Photo 2b). The disintegrated bundles, weighing 10–15 g, were collected in bouquets covered with lids, and moisture was found by the requirements for determining the natural soil moisture. 10 plastic limit tests were done in total.

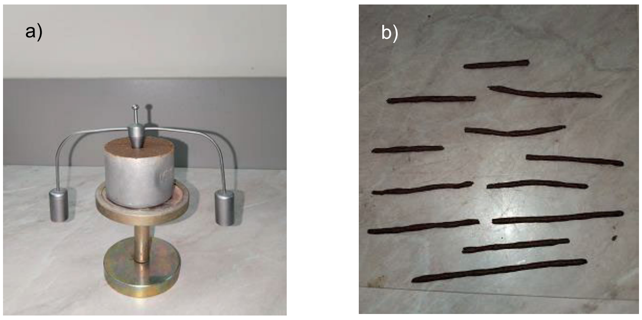

Photo 2. Determination of: a) liquid limit by the balanced cone method and b) plastic limit by the rolling method (phot.: *Zh. Kusbergenova*)

VAPOUR EQUILIBRIUM METHOD WITH THE WATER ABSORPTION MEASUREMENT

The method of vapour equilibrium (ASTM E 104 – 02) with sodium chloride (NaCl) and potassium chloride (KCl) salts was applied to determine the sorption properties and equilibrium moisture content of soils modified with xanthan gum, chitosan, and carboxymethylcellulose. NaCl and KCl solutions were used to simulate ionic environments commonly found in natural subsurface systems. Sodium and potassium are abundant cations, especially in environments affected by seawater influence or long-term fluid-rock interactions. The concentrations chosen in the lab were representative of the range observed in field conditions, including groundwater with moderate salinity and formation waters. A total of 20 soil samples were prepared for the study, including 18 modified samples and 2 unmodified (control) samples. A solution of the selected salt was prepared in a plastic container. 100 g of salt was added to 200 cm^3 of distilled water. Then, the plastic container was placed on the bottom. To recreate the effect of suspending soil samples above the container with salt, a mesh board crossbar of the same size as the bottom of the container was placed on top of the container. Then, soil samples, previously stored in plastic moulds, measuring 80 mm in diameter and 20 mm in height, were placed on top (Photo 3). Samples were stored in a climate chamber at a stable temperature (25 ±1°C) and relative humidity (60 ±3%).

The samples were incubated in airtight chambers over a saturated potassium chloride solution in one container and a saturated sodium chloride solution in the other. There were nine modified samples and one unmodified sample in each container, ensuring that comparisons could be made under identical conditions. The weight of the samples was recorded daily over 10 days. During the testing period, moisture measurements were made sequentially: first, using a moisture sensor for continuous monitoring without destroying the sample, and then, by weighing, i.e., determining the weight using a scale. The stationary sensor used for the test was made of wear-resistant polycarbonate and acrylonitrile butadiene styrene. The sensor has two highly sensitive extended probes, enabling faster and more accurate moisture detection. To ensure reliable readings, the sensor was calibrated by comparing its readings to the gravimetric water content of the soil. The sensor was inserted approximately 20 mm into the soil sample during measurements.

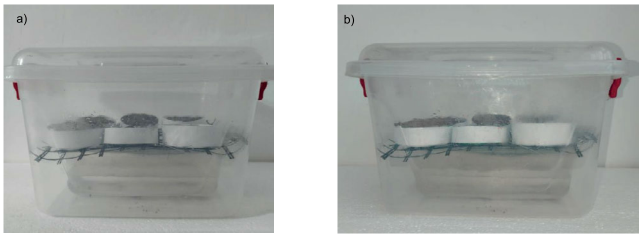

Photo 3. Specimens in the container: a) before and b) during the test (phot.: *Zh. Kusbergenova*)

RESULTS AND DISCUSSION

RESULTS OF SCANNING ELECTRON MICROSCOPE (SEM) ANALYSIS

When mixed with the soil, carboxymethylcellulose (CMC) formed a gel-like and viscous structure with moderate water binding capacity (Khodabandeh, Nagy and Török, 2023). In SEM images, CMC showed a smoother structure than xanthan gum (XG) but with a less pronounced gel network (Photo 4a-c). The soil structure was more friable when interacting with CMC than unmodified soil (Photo 5d). When mixed with the soil, XG formed a dense and stable gel-like structure, seen in the SEM images (Photo 4d-f) as uniformly distributed granules, with a network of molecules linking the soil particles (Hassanisaadi *et al.*, 2024).

The images showed (Photo 5a-c) well-organised structures with high viscosity, characteristic of gels formed during hydration (Simelane *et al.*, 2022). In the case of the CH stabiliser, the larger and more irregularly distributed granules indicate a less stable structure of the matrix (Photo 5a-c) than the XG (Fatehi *et al.*, 2024). As a biopolymer with antimicrobial properties and the ability to form aqueous solutions (Tasuji *et al.*, 2024), CH formed looser, not as compacted structures, compared to XG (Dehghan *et al.*, 2019).

Scanning electron microscope images revealed generally a denser and more cohesive microstructure with improved particle bonding and reduced pore spaces, particularly in treated samples. Furthermore, the tighter microstructure limits water pressure and particle detachment, thereby increasing erosion resistance.

RESULTS OF LIQUID AND PLASTIC LIMITS TESTS

It was revealed that the liquid limit for soil modified by CMC, XG, and CH biopolymers was lower than for the US after mixing; however, it increased with the time of curing and became greater after two days (Fig. 1). A lower liquid limit indicates that

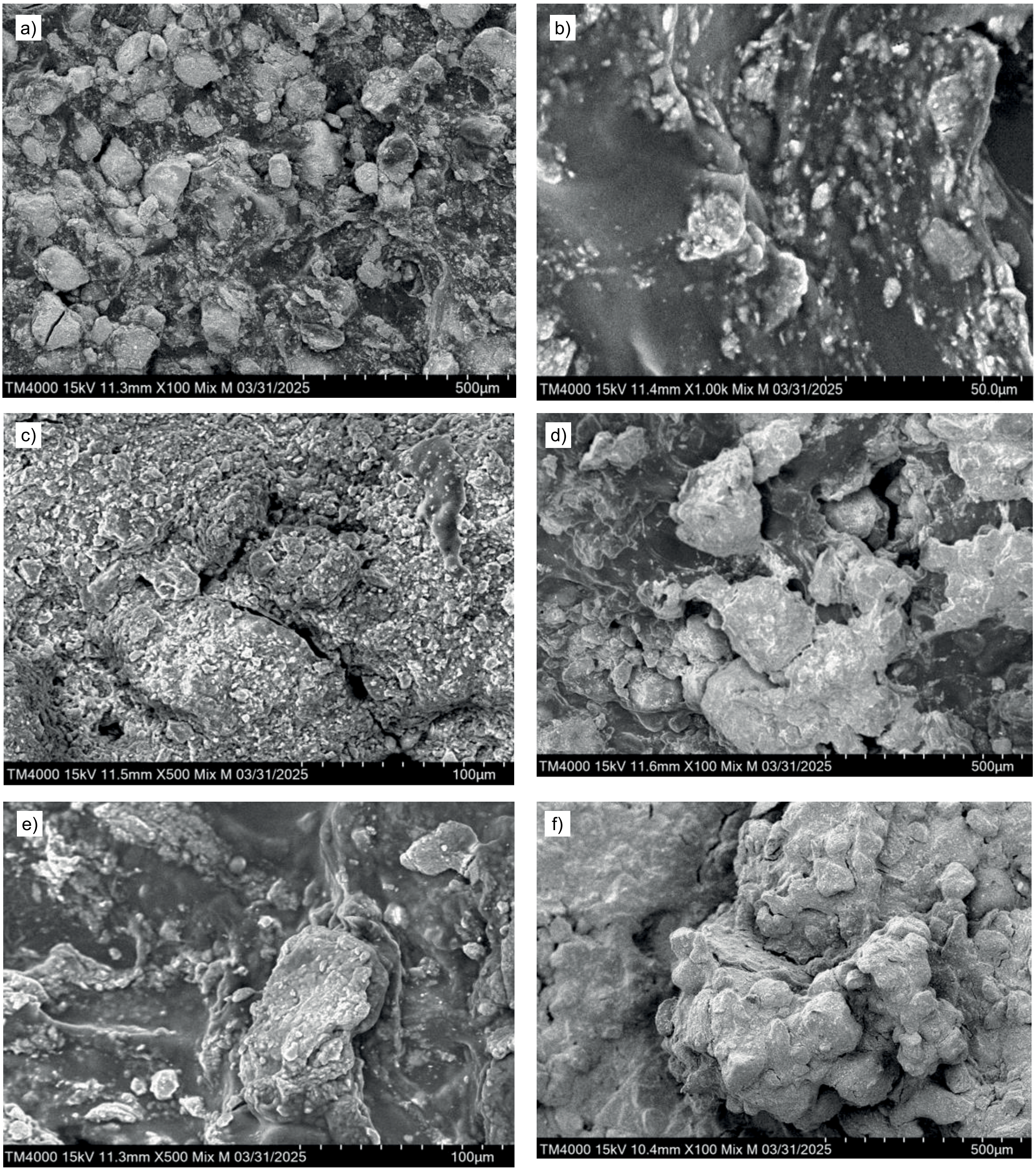

Photo 4. Results of scanning electron microscope analysis of the tested soil using carboxymethylcellulose (CMC) in concentrations of: a) 1%, b) 2%, c) 3%, and xanthan gum (XG) in concentrations of: d) 1%, e) 2%, f) 3% (phot.: *Zh. Kusbergenova*)

introducing these additives decreases the liquidity of the soil exactly after mixing. In contrast, the plastic limit for all stabilisers was greater than that of the soil without biopolymers after mixing (Fig. 2).

At the initial stage (0 days), liquid limit values of XG, CH, and CMC were significantly lower than those of the untreated soil (US), indicating that the uncured soil samples had not yet developed a stable polymer–particle structure. After two days of curing, the liquid limit increased significantly for all biopolymer-treated soils, approaching or even slightly exceeding the untreated soil, which reflects polymer hydration and the onset of interparticle bonding. The interpolated results at four days confirmed a gradual upward trend, suggesting a progressive stabilisation process within the soil–polymer matrix. By the 6th day, liquid limit values of XG and CMC were greater than those of the untreated soil. At the same time, CH showed moderate growth, highlighting the variability of biopolymer efficiency depending on type and dosage. Compared to the untreated soil, which remained constant at 19.357%, the uncured soil samples demonstrated that polymer addition led to an initial decrease in liquid limit

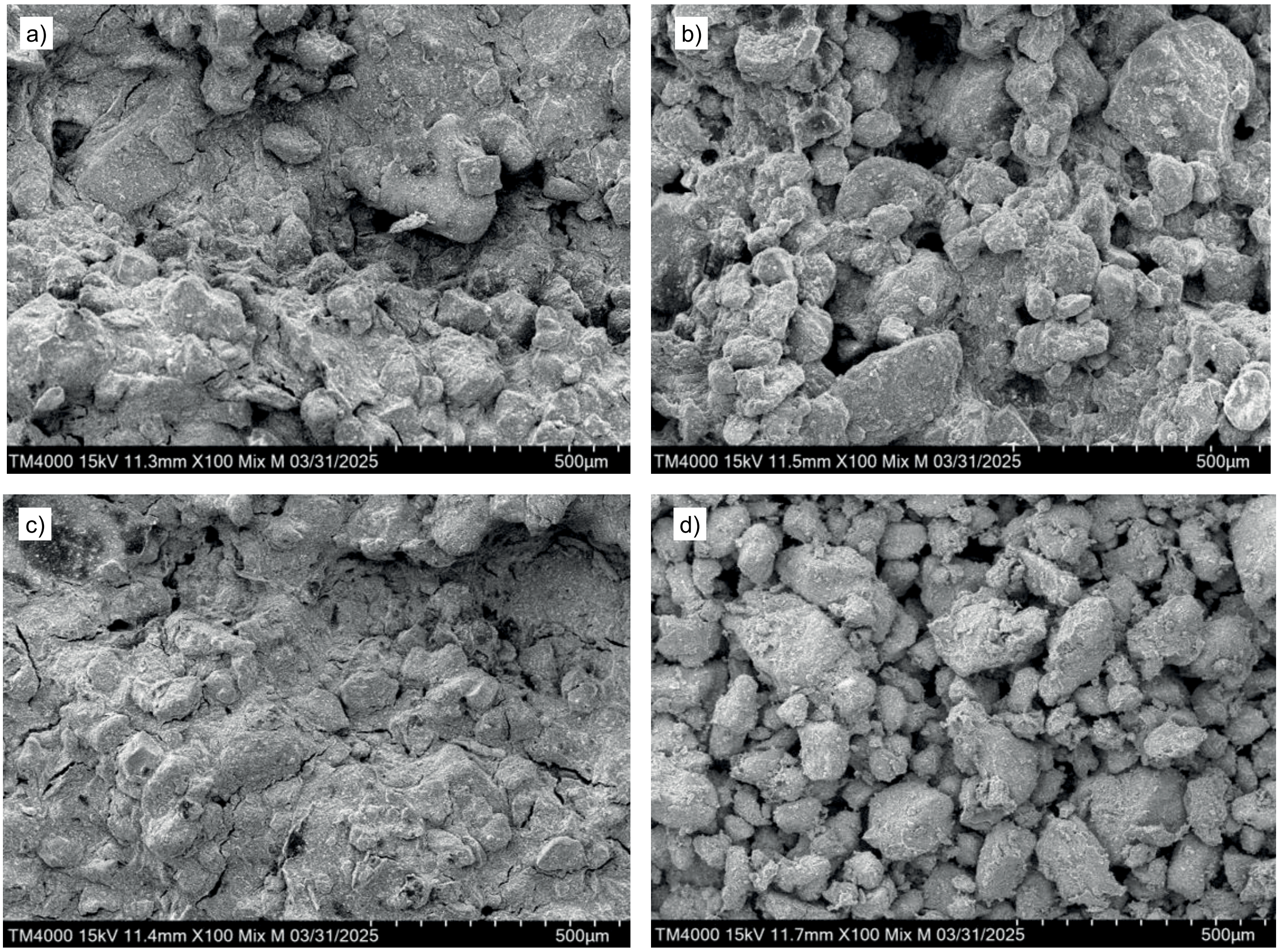

Photo 5. Results of scanning electron microscope analyses of the tested soil with chitosan (CH) in concentrations of: a) 1%, b) 2%, c) 3% and d) unmodified soil (phot. *Zh. Kusbergenova*)

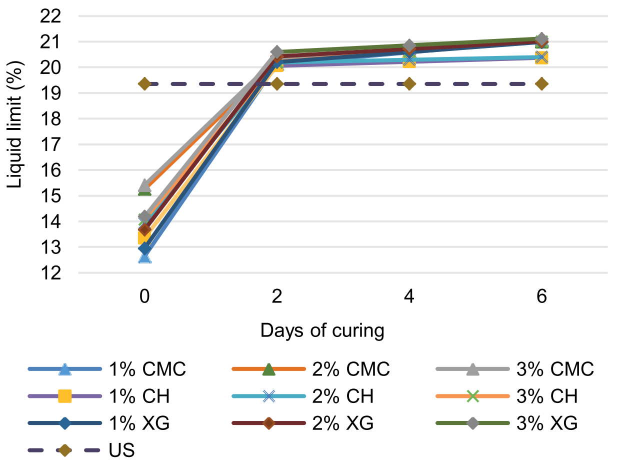

Fig. 1. Change of the liquid limit depending on the number of days of curing for different biopolymers (Vasiliev's cone); CMC, CH, XG, US as in Photo 1; source: own study

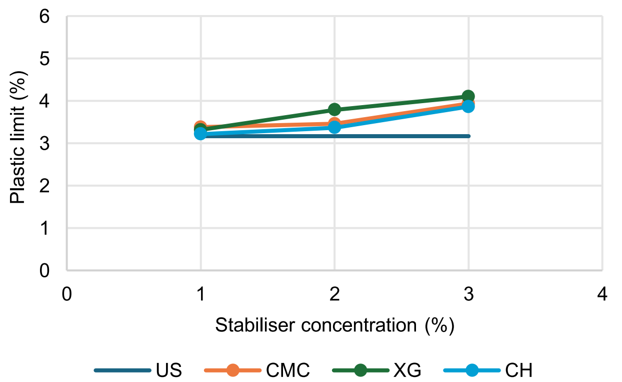

Fig. 2. Change of the plastic limit depending on the stabiliser concentration; US, CMC, XG, CH as in Photo 1; source: own study

immediately after mixing (0 days), but the cured samples showed improved water resistance and stable structure. Overall, the observed behaviour confirms that biopolymer stabilisation is a curing-dependent process, where liquid limit is as a sensitive indicator of the evolving soil–polymer interactions.

The slight increase in plastic limit with a decrease in liquid limit after mixing indicates a narrowing of the plasticity range regardless of biopolymer type and dosage. However, that increased tendency to transition into the liquid state decreases with time as the liquid limit grows.

RESULTS OF VAPOUR EQUILIBRIUM METHOD

The moisture content of biopolymers-stabilised soil, measured under vapour equilibrium conditions established using potassium chloride in one case and sodium chloride in the other, for all biopolymers and salts, was greater than for unmodified soil. However, its rise was affected by the dosage of biopolymers. For potassium chloride, in the case of CH, the values gradually increased in 3–4 days, indicating that the moisture absorption index grows with increasing amount of added biopolymer (Ni, He and Geng, 2024) (Fig. 3). Similarly, for XG, there was also a rising trend with increasing proportion, and the change was slightly greater than for CH, indicating a more pronounced effect of this biopolymer on the soil (Lang *et al.*, 2024). An increase in the ratio was also seen in the case of CMC in 3–4 days. However, differing from XG and CH, it was sharper, indicating that CMC is particularly effective in improving soil properties at a particular dosage. At the same time, XG and CH showed a more uniform increase. In all cases, increasing the biopolymer content improves the performance of the soil, with CMC proving to be the most effective additive when using 2 or 3% per dry soil weight. The moisture content reached its plateau for about 120 h. It stabilised at 60% for XG and CH and about 80% for CMC.

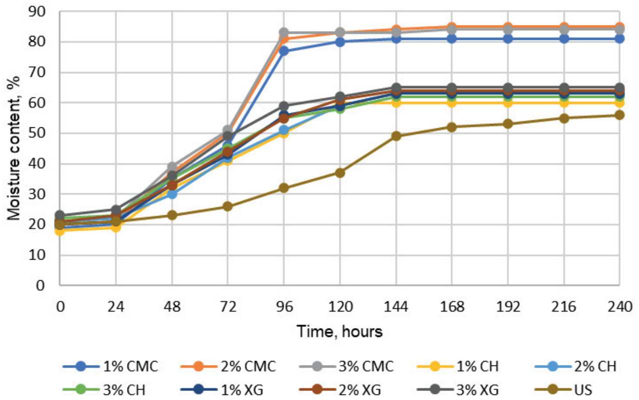

Fig. 3. Change of the soil moisture content depending on biopolymers when saturated with potassium chloride salt; CMC, CH, XG, US as in Photo 1; source: own study

The increase in moisture content in 3–4 days (Fig. 3) was observed in all samples, regardless of the kind of biopolymers and their dosage; however, there was a steep rise between three and four days in the case of CMC. Therefore, the amount of growth can be associated not with the concentration itself, but with time and accumulated exposure to moisture. This jump observed for CMC was due to the transition of CMC into a gel-like state after a certain time of interaction with water. At the early stage (up to three days), the biopolymer partially limited the capillary penetration of moisture. However, as it becomes saturated and partially swollen, its structure becomes less stable, resulting in a sudden increase in water permeability. This effect may also be related to localised gel structure disruption or moisture redistribution in the pore space.

Experimental data showed that all three biopolymers, CMC, CH and XG, when using potassium chloride salt, contributed to the increase in the value of the moisture content and soil weight within 10 days, while the nature of the change depended on the type of biopolymer and dosage (Fig. 4). When CMC was used, the most marked increase occurred at the dosage of 3%, where the value reached 143.8 g. CH supplementation showed a more pronounced increase, especially at 2 and 3%. Rising significantly until the end of the observed period, it reached a maximum (163.1 g) at 3% by 240 h. It indicates the high efficiency of CH, probably related to its cationic nature. XG showed intermediate values between CMC and CH. The most significant growth was observed at 3%, when mass increased to 163 g by 240 h. The rate of change was smooth, with a pronounced effect between 72 and 120 h.

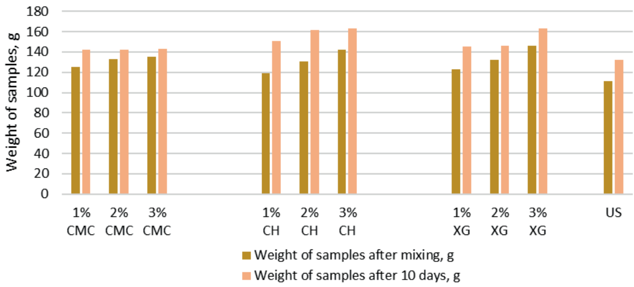

Fig. 4. Change of the weight of samples using potassium chloride salt for the vapour equilibrium method; CMC, CH, XG, US as in Photo 1; source: own study

Thus, the most significant effect was observed when CH was applied at a dosage of 3%, followed by XG 3% and CMC 3%. The main increase phase of all stabilisers occurred at 72–96 h, after which the parameters stabilised.

Tests have revealed that CMC, CH and XG had different effects on soil water saturation over time when using the sodium chloride salt for the vapour equilibrium test (Fig. 5).

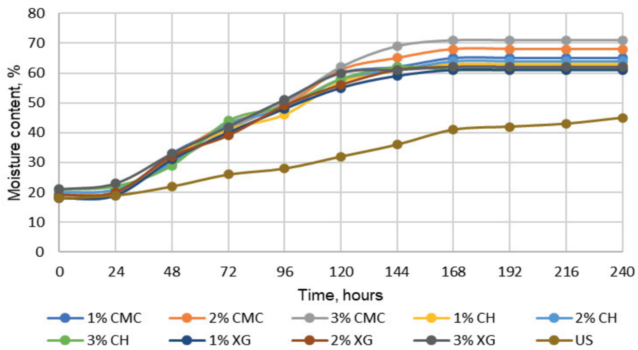

Fig. 5. Change of the soil moisture content with biopolymers when saturated with sodium chloride salt; CMC, CH, XG, US as in Photo 1; source: own study

All additives increased the water content, but the biopolymer type and dosage affected the rate of change and maximum values. CMC provided the greatest degree of saturation. At a dosage of 3%, the moisture content increased from 20 to 71%, with active growth up to 120 h, followed by stabilisation. CH showed smoother dynamics: at 3%, saturation reached 64%, with a significant increase up to 144 h and then levelling off. XG showed a similar pattern of change to CH: at 3%, values increased from 21 to 62% by 168 h, then stabilised. Thus, the maximum water saturation was observed when CMC was applied at a dosage of 3% due to its high hydrophilicity. The most active phase of water saturation for all additives was 48–120 h, after which stabilisation occurred.

Within 10 days, there was an increase in the mass of soil samples due to moisture absorption with sodium chloride salt (Fig. 6). The most tremendous increase in mass was recorded when using CMC, especially at a dosage of 3%, with an increase from 134 to 171 g. CH provided a smoother growth in mass. At a dosage of 3%, the mass increased from 131 g to 145 g. XG showed intermediate results; at 3%, the mass rose from 128 g to 150 g. Thus, stabilisers contribute to moisture absorption, CMC being the most effective. The main phase of mass gain for all additives was observed between 48 and 144 h, after which saturation and mass stabilisation occurred.

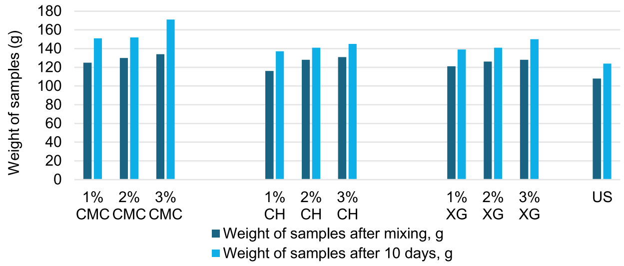

Fig. 6. Change of the weight of samples using sodium chloride salt for the vapour equilibrium method; CMC, CH, XG, US as in Photo 1; source: own study

CONCLUSIONS

Based on the laboratory research, it was established that adding xanthan gum (XG), chitosan (CH), and carboxymethylcellulose (CMC) leads to a modification of the Atterberg limits and structure of heavy sandy clay loam.

All biopolymers except CH (1 and 2%) showed a similar value of the liquid limit after six days of stabilisation, equal to about 21%. The increase in the liquid limit from the 2^{nd} to the 6^{th} day of stabilisation indicates that the soil transitions into a liquid state with more difficulty, as the biopolymers retain moisture within the soil. Moreover, an increase in the plastic limit points to a wider transition range from brittle to plastic state, during which the soil requires more water.

Among the presented biopolymers, the best result in water saturation was shown by CMC in proportions of 1, 2, and 3% when the modified soil was saturated with potassium chloride salt and also with sodium chloride salt.

Potassium chloride salt increased the weight over 10 days for all types of biopolymers. The most notable increase was observed with a 3% concentration of CH, followed by 3% XG and 3% CMC. All stabilisers exhibited peak activity between 72 and 96 h, after which the mass of modified soil stabilised, suggesting that the completion of the stabilisation process main phase within this time.

The results revealed that sodium chloride also promotes moisture absorption in modified soil samples over 10 days, increasing their mass. The most significant effect was observed with the addition of 3% CMC, suggesting that this biopolymer enhances the soil's capacity to retain moisture, thereby contributing to greater mass gain.

There is a need for further research into verifying the obtained results of water retention and plasticity of soil modified with 3% CMC in the field tests and their mechanical properties before applying it in engineering practice. The obtained results also provide a scientific basis for the development of digital simulation tools focused on the behaviour of biopolymer-stabilized soils under water-related conditions.

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interest.

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