Mechanical response and biodegradation of CMC-modified loam under constant-volume conditions during saturation

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Abstract. The use of water-soluble biopolymers as a sustainable alternative to conventional soil improvement in geotechnical engineering is gaining increasing attention. Their mechanical behaviour strongly depends on the degree of saturation: while biopolymer-treated soils may behave in a brittle manner at low water contents, high saturation levels promote biopolymer swelling and the formation of viscoelastic gel structures. Despite their relevance, saturation-dependent responses and polymer-soil interaction mechanisms are not yet sufficiently understood. This study investigates the biopolymer carboxymethylcellulose (CMC) with varying chain lengths and degrees of *substitution, applied to a low-plasticity clay. Specimens were compacted to maximum dry density to reflect practical geotechnical boundary conditions. The evolution of total vertical stress was monitored under constant-volume conditions during saturation over a period of approximately 70 days. Potential biodegradation of the biopolymer during testing was assessed using loss-on-ignition (LOI) measurements and rheological analyses performed before and after hydro-mechanical loading. The results indicate that both the mechanical response and biodegradation behaviour of CMC-modified soils are strongly coupled and primarily governed by soil fabric, polymer-soil binding mechanisms, water uptake capacity, and biopolymer composition.

1 Introduction

Polymers offer innovative solutions in geotechnical engineering, such as reducing permeability in saline conditions [1], controlling erosion [2] and improving crack resistance [3] for soil stabilisation. Their mechanical behaviour is strongly influenced by water content, resulting in a transition from stiff, solid-like responses at low hydration levels to increasingly ductile behaviour as the water content rises [4]. Therefore, the hydraulic behaviour of polymer-modified soils is crucial for controlling their mechanical performance and must be considered alongside polymer-soil interactions.

While biopolymers are environmentally attractive, they are inherently susceptible to biodegradation [5]. While this limits their long-term applicability, it enables short-term geotechnical applications, such as temporary construction measures or slope stabilisation systems that are subsequently replaced by natural reinforcement [6]. A fundamental understanding of biodegradation mechanisms and their impact on hydro-mechanical behaviour is essential to clearly define these application ranges.

1.1 Background and motivation

1.1.1 Volumetric behaviour polymer-modified soils

The volumetric behaviour of soils is a fundamental parameter in geotechnical engineering, as volume changes directly affect stress states and mechanical performance. It is primarily governed by the hydraulic properties of the soil, which are commonly described by soil-water characteristic curves (SWCCs) for both natural and polymer-modified materials [7, 8].

Upon saturation, water uptake induces volumetric expansion. Under free-swell conditions, this expansion manifests as an increase in volume, whereas under constant-volume conditions it results in the development of stresses. This volumetric behaviour is particularly relevant for sealing systems such as liners and barrier layers. Moderate swelling reduces hydraulic conductivity, promotes crack closure, and enhances self-healing capacity. In contrast, excessive expansion may cause heave and impair structural integrity.

The volumetric response of polymer-modified bentonites has been widely investigated, often using the free swell index as a simplified indicator of expansion potential. The effectiveness of polymer modification strongly depends on the chemical environment. Anionic polymer-modified Na-bentonites show increased swelling under low-salinity conditions, while at elevated $CaCl_2$ concentrations (> 500 mM) their swell index may fall below that of unmodified bentonite [9-11]. Under constant-volume saturation, the resulting stress level is additionally controlled by dry density. A pronounced increase in vertical stress due to anionic polymer modification is observed at low dry densities, whereas at high densities the effect becomes negligible [12, 13]. Furthermore, the mechanical response of polymer-

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modified soils is strongly influenced by mineralogy. Depending on the dominant minerals present, polymer addition may enhance or reduce compressibility under saturated conditions [12, 14].

While these findings provide valuable insight into polymer modified highly swellable clay systems, the evolution of total vertical stress during saturation under constant-volume conditions is also critical for soil stabilisation in earth dams. Under constant-volume conditions, wetting-induced swelling may generate additional internal stresses, influencing crack healing [15] and long-term hydraulic performance [16]. Polymers can potentially mitigate these effects by enhancing soil cohesion [2] and promoting self-healing [3]. To isolate polymer-induced contributions to total stress evolution from the soil's intrinsic behaviour, this study employs a low-swelling loam. Constant-volume saturation tests are conducted to determine the stress evolution with increasing water content, while amplitude sweep tests characterise the intrinsic stiffness of the pure polymer phase. This combined approach enables differentiation between soil-structural and polymer-network effects during wetting.

1.1.2 Biodegradation assessment in polymer-soil composites

Given the use of a biopolymer, potential biodegradation processes must be considered when analysing the hydro-mechanical behaviour of polymer-modified soils. Biodegradation may alter both polymer content and polymer-soil interactions, thereby directly affecting the mechanical response during saturation. Quantifying these processes requires methods capable of determining polymer content within polymer-soil composites and distinguishing between different polymer states.

Several approaches to quantifying polymers in bentonite have been proposed in the literature. [17] investigated polymer loading in bentonite-polymer composites using a component-based method to analyse loss-on-ignition (LOI) but demonstrated that the results can be biased due to the influence of bentonite on the thermal degradation of polymers during heating. Nevertheless, LOI-based component methods have been successfully applied in other studies [10], indicating their continued relevance when interpreted carefully.

Beyond solid-phase analysis, [18] proposed a complementary approach for quantifying residual polymer concentrations in polymer-bentonite fluids. After centrifugation, the supernatant, which contained primarily free polymer, was analysed using total organic carbon (TOC) testing, UV spectroscopy and viscosity measurements. Rheological measurements showed the highest repeatability. It should be noted, however, that polymer concentrations determined from the supernatant represent only freely dissolved polymer, while soil-bound polymer remains in the sediment.

The objective of this study is to quantify potential biodegradation occurring over the duration of the constant-volume saturation tests and to couple these processes with the observed hydro-mechanical response. To this end, LOI measurements are combined with centrifugation-based separation and rheological investigations. This combined methodology enables not only the assessment of changes in total polymer content, but also the differentiation between free and soil-bound polymer fractions and the identification of degradation-related changes in polymer-soil binding mechanisms.

2 Material and methods

2.1 Soil and biopolymer

The material used in this study is a commercially available soil (Baulehm (loam), manufacturer: Claytec). Based on the grain size distribution shown in Fig. 1, the soil is classified as a silt. However, according to the Atterberg limits and its position in the Casagrande plasticity chart (Fig. 2), the loam (denoted as Ref.) is classified as a low-plasticity clay TL (I_P = 11.2%, w_L = 30.5%). The specific gravity of the soil is G_s = 2.693.

The biopolymer used is carboxymethylcellulose (CMC), a cellulose derivative obtained from Thermo Fisher Scientific. Three CMC variants were investigated: two short-chain (S) polymers with a molar mass of 250,000 g/mol and one long-chain (L) polymer with a molar mass of 700,000 g/mol. Two polymers have a degree of substitution (DS) of 0.9, while one has a DS of 1.2. The DS denotes the average number of hydroxyl groups per anhydroglucose unit substituted by carboxymethyl groups and is known to influence biodegradability, with higher DS values exhibiting reduced biodegradation rates [19]. The investigated polymers are referred to as CMC-L0.9, CMC-S0.9, and CMC-S1.2.

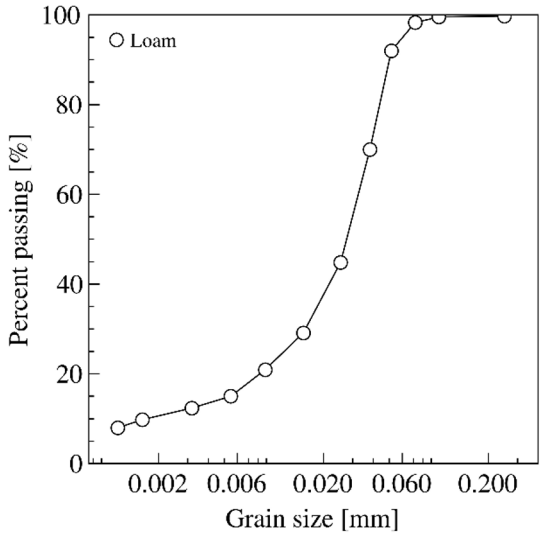

Fig. 1. Particle size distribution of the loam.

2.2 Material preparation

Previous studies have demonstrated that the adsorption behaviour of biopolymers is strongly influenced by mixing and preparation procedures, which subsequently affect the macroscopic properties of soil-biopolymer composites [7, 12, 20-22]. However, several of these preparation methods are only feasible in a laboratory setting due to the significant technical effort involved and their limited practical applicability. To investigate

soil-biopolymer interactions under conditions closer to field application, this study adopted a dry-mixing method. In this approach, 2 wt.% of CMC, relative to the dry mass of the clay, was added to the soil at its hygroscopic water content. The dry soil and biopolymer were first thoroughly homogenised before water was added to the mixture.

Fig. 2 shows the Casagrande plasticity chart for the untreated loam used as reference soil (Ref.) and the CMC-modified variants. A pronounced increase in the liquid limit w_L is observed for all polymer-treated samples, with values rising by at least a factor of 1.5 compared to the unmodified loam. Consequently, the samples modified with CMC-S0.9 and CMC-S1.2 are classified as medium-plasticity clays (TM) in the Casagrande diagram, while the sample treated with CMC-L0.9 is classified as a high-plasticity clay (TA).

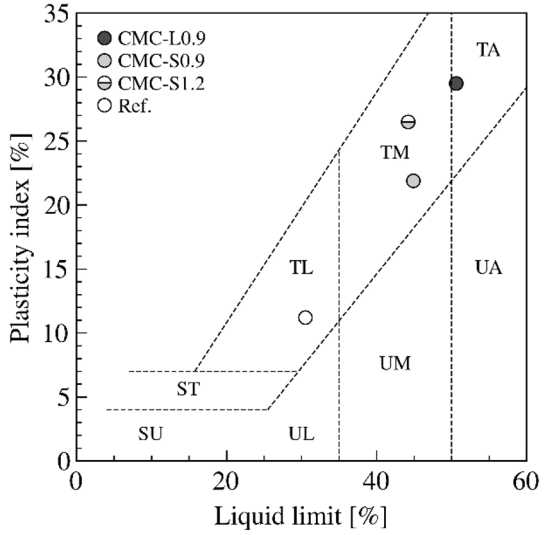

Fig. 2. Casagrande plasticity chart for unmodified and CMC-modified loam.

2.3 Constant-volume saturation tests

Constant-volume saturation tests were conducted using a rigid-wall swelling pressure cell [23]. Cylindrical specimens with 20 mm in height and 50 mm in diameter, were placed inside the cell. Porous stones were placed in the top and bottom caps to allow saturation from below while enabling the drainage of excess water.

Two specimen preparation procedures were employed. In the first approach, the material was compacted in cylindrical moulds at its respective optimum water content (OWC), which was determined from Proctor tests. Static compaction was applied to achieve the maximum dry density, thereby ensuring geotechnically relevant boundary conditions. The corresponding compaction parameters are summarised in Table 1. After compaction, the specimens were oven-dried at 60 °C and subsequently installed in the swelling pressure cell in a dry state. In the second approach, specimens were compacted following the same procedure. However, instead of being dried, they were placed directly into the swelling pressure cell at optimum water content. Upon installation, an initial contact stress of approximately 125 kPa was applied to ensure full contact between the specimens and the cell caps. This stress corresponds to less than 15% of the compaction pressure, ensuring that swelling developed under overconsolidated conditions. In both procedures, the tests were initiated by saturating the samples via the bottom cap, with a hydrostatic pressure of about 3 kPa during hydration. The evolution of total vertical stress was continuously recorded using a load cell.

Table 1. Optimum water content and maximum dry density for unmodified and CMC-modified loam.

Modification	OWC (%)	$\rho_{d,max}$ (g/cm³)
CMC-L0.9	21.0	1.550
CMC-S0.9	19.0	1.645
CMC-S1.2	20.5	1.625
Ref. (Loam without CMC)	14.0	1.800

2.4 Characterisation of pure CMC and polymer-soil composites upon hydration

Amplitude sweep tests were conducted on pure CMC gels prepared at polymer-to-water ratios corresponding to the optimum water content (OWC) and the fully saturated state that is reached during constant-volume saturation tests. Measurements were performed using an MCR 301 rheometer (Anton Paar) with 25 mm plate-plate geometry at a temperature of 25 °C. The gap was set to 1 mm and trimmed after loading to ensure reproducible boundary conditions. A resting time of 1 min was allowed for structural relaxation prior to measurement. Storage (G') and loss (G'') moduli were recorded over a strain range of $\gamma = 10^{-2}\% - 10^{3}\%$ at a constant angular frequency of $\omega = 10$ rad/s to capture the linear viscoelastic (LVE) regime. LVE parameters (G_0' and G_0'') and the loss factor ($\tan\delta = G_0''/G_0'$) were subsequently determined. In addition, water uptake capacity of both unmodified and polymer-modified soil samples was measured according to DIN 18132 over 24 h. Evaporation rates were corrected following [24].

2.5 Biopolymer content quantification

Following the hydromechanical testing period of ~70 days, CMC degradation and leaching were quantified for the samples that were initially prepared in a dried state. Specimens were halved: one half was analysed for loss on ignition (LOI, DIN EN 17685-1) on three subsamples to assess polymer content in the soil composite. The other half was dispersed in ~10 × w_L water for 16 h, then centrifuged (15,000 rpm, 30 min), yielding a sediment (soil-bound polymer) and supernatant (free polymer). Both phases were oven-dried (105 °C) and LOI was determined to quantify polymer mass fractions in each phase. The viscosity-shear rate behaviour of the supernatants was measured using an MCR 102e rheometer (Anton Paar) with double-gap cylinder geometry, suitable for viscosities from 1 to 10^8 mPa·s. All measurements were performed at a temperature of 25 °C, and viscosity was recorded as

a function of shear rate over the range $\dot{\gamma} = 10^{-2}$-10^{4} s^{-1}. These measurements provided additional insight into polymer degradation, as viscosity is highly sensitive to concentration and molecular chain length. All analyses were also conducted on the initial material, allowing comparison between initial and post-test states to identify potential degradation mechanisms.

3 Results

3.1 Temporal total vertical stress evolution

Fig. 3 illustrates the temporal evolution of the total stress for the untreated loam and the CMC-modified loam variants that were dried before testing. Load cell measurements are presented as total vertical stress changes $\Delta\sigma_v$ relative to the initial stress of 125 kPa, with positive values indicating an increase and negative values a decrease relative to the initial stress state. The reference sample without polymer exhibits an initial increase in total stress, reaching a maximum increase of about +30 kPa after 10 minutes. This behaviour may be attributed to hydration-induced swelling of the clay fraction. Subsequently, the stress gradually declines, stabilising after ~500 minutes at approximately 20 kPa below the initial stress, likely due to time-dependent microstructural rearrangements within the soil matrix. These relatively low stresses allow the volumetric effect of polymer addition on the soil matrix to be isolated. In contrast, all CMC-modified specimens display a markedly different total stress evolution compared to the unmodified loam, though they share a qualitatively similar trend. The response is characterised by an initial total stress decrease, followed by a slight recovery and a more pronounced decrease after ~600 minutes. Negative total stress changes (i.e. relaxation) indicate a structural collapse during saturation. Among them, specimens CMC-S0.9 and CMC-L0.9 show nearly identical responses, with overlapping stress-time curves. The CMC-S1.2 specimen exhibits a systematic shift toward higher stresses, resulting in a smaller initial stress drop and higher stresses throughout the test.

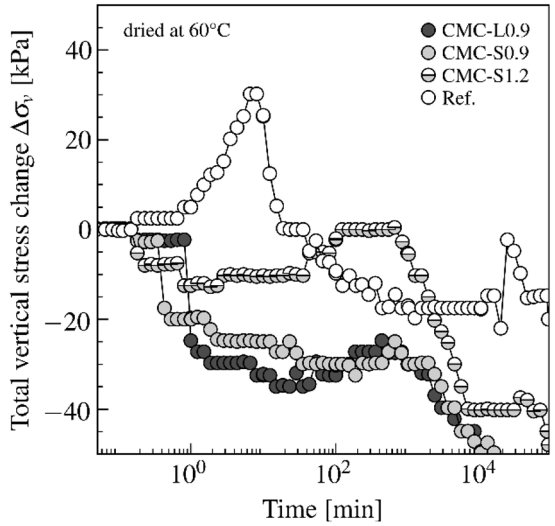

Fig. 3. Temporal evolution of the total vertical stress change in unmodified and CMC-modified loam starting from the dried state.

In addition, Fig. 4 shows the temporal evolution of total stress for samples inserted at the OWC in the swelling pressure cell. Overall, the evolution of total stresses follows a similar trend. However, the reference sample exhibits a noticeably smoother evolution compared to the sample initially in the dried state, reaching a peak of only +7 kPa. For the CMC-modified samples, higher total stresses are observed compared to the initially dried specimens, following the order CMC-L0.9, CMC-S0.9, and CMC-S1.2. However, the total stress peaks occur significantly later, approximately 3000 minutes after the start of the experiment, compared to the dried samples. This indicates that the initial water content strongly influences both the magnitude and temporal evolution of stress in CMC-modified loam.

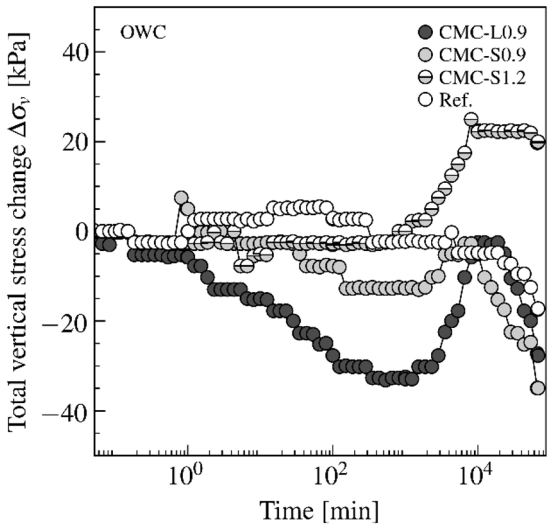

Fig. 4. Temporal evolution of the total vertical stress change in unmodified and CMC-modified loam starting from the OWC.

3.2 Viscoelastic behaviour of the biopolymers

Amplitude sweep tests reveal viscoelastic behaviour of the pure CMC biopolymer variants isolated from the soil matrix. Fig. 5 shows the storage (G') and loss (G'') moduli for the polymer-to-water ratio in the OWC and saturated states. In all cases, $G_0' > G_0''$ ($\tan\delta < 1$), which confirms viscoelastic solid behaviour (Table 2). Both G_0' and G_0'' decrease from CMC-L0.9 to CMC-S0.9 and CMC-S1.2. Furthermore, all polymers exhibit a marked reduction in stiffness from OWC to saturated state, accompanied by an increase in $\tan\delta$, reflecting a shift toward less elastic-dominated behaviour upon hydration.

Table 2. Storage modulus G_0', loss modulus G_0'', and loss factor $\tan\delta$ of pure CMC variants.

Biopolymer	State	G′₀ [kPa]	G″₀ [kPa]	tan δ [-]
Pure CMC-L0.9	OWC	5.4	1.8	0,33
	saturated	2.9	1.2	0,41
Pure CMC-S0.9	OWC	3.0	1.3	0,44
	saturated	1.4	0.8	0,54
Pure CMC-S1.2	OWC	1.6	0.9	0,55
	saturated	0.7	0.5	0,68

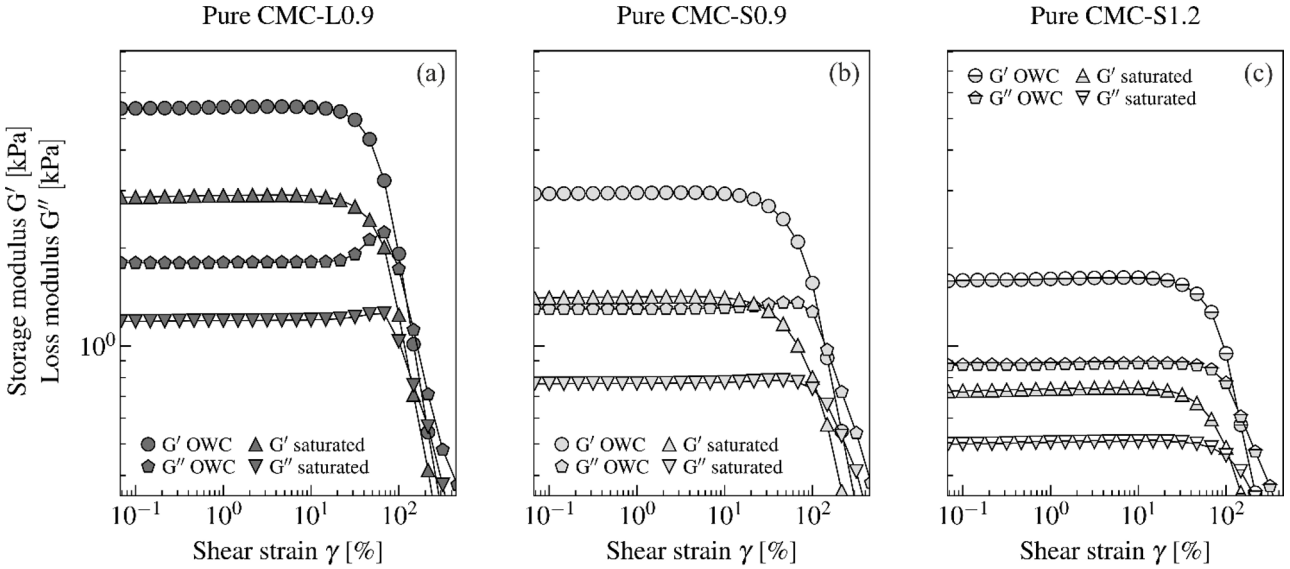

Fig. 5. Storage modulus (G′) and loss modulus (G″) as functions of shear strain for (a) pure CMC-L0.9, (b) pure CMC-S0.9, and (c) pure CMC-S1.2.

These observations suggest that the initial decrease in total stress upon hydration in CMC-modified loam (Fig. 3 and 4) may be attributed to the polymer becoming increasingly ductile as saturation progresses, potentially allowing partial collapse of the pore space. However, CMC-L0.9, despite its highest stiffness and lowest loss factor, does not show the smallest total reduction, indicating that viscoelastic properties alone cannot fully explain the observed total stress evolution.

3.3 Water-uptake of biopolymer modified loam

Fig. 6 shows the maximum water uptake after 24 h as a function of the liquid limit. A nearly linear correlation is observed, indicating that soils with higher liquid limits absorb more water. Compared to the untreated loam, all CMC-modified samples exhibit increased water uptake. The additional water uptake may be governed by the osmotic pressure that arises immediately upon contact of the polymer with water [25]. Among the polymer-treated specimens, CMC-L0.9 shows the highest water uptake, exceeding that of the shorter-chain variants CMC-S0.9 and CMC-S1.2. This trend is consistent with previous investigations on soil-water characteristic curves, which demonstrated that longer polymer chains enhance water retention over the entire suction range [13]. The increased water uptake promotes volumetric expansion. Under constant-volume saturation conditions, this expansion likely contributes to a gradual increase in total stress (Fig. 3 and 4). However, despite continued water absorption, the reduction in polymer stiffness (Fig. 5) may limit mechanical resistance and lead to a subsequent decrease in total stress (Fig. 3 and 4).

Furthermore, it should also be noted that CMC-L0.9 was tested at a lower dry density than the shorter-chain CMCs (Table 1). This increased pore space allows the hydrating polymer to alleviate externally applied hydro-mechanical stresses by expanding into the available voids. Thus, although CMC-L0.9 exhibits a stiffer material response than the shorter-chain CMCs (Fig. 5), stronger hydration and the increased void space between the soil particles may reduce the overall total stress development.

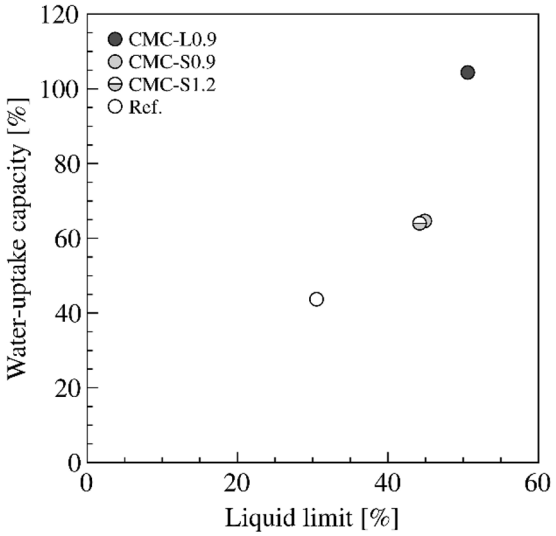

Fig. 6. Maximum water uptake after 24 h as a function of the liquid limit for unmodified and CMC-modified loam.

3.4 Biopolymer loss and CMC-soil binding mechanism

As the constant-volume saturation test was conducted over an extended period of approximately 70 days, potential degradation effects of the biopolymer had to be quantified. For this purpose, LOI measurements and rheological tests were employed.

The LOI values of the pure biopolymers, the pure loam and the biopolymer-soil composites (BSC) in the initial state and post-test state were determined and are summarised in Table 3. However, the primary focus of this study is not the total LOI of the BSC, but rather the fraction of LOI attributable solely to the polymer. This polymer-related LOI can be determined using Equation (1).

Table 3. LOIs of the pure CMC variants, the pure loam and the CMC-modified loam in the initial state and post-test state.

Material	LOI polymer/soil [%]	LOI BSC, initial [%]	LOI BSC, post-test [%]
CMC-L0.9	78.76	2.86	2.52
CMC-S0.9	78.55	2.94	2.50
CMC-S1.2	74.73	2.67	2.21
Loam	1.66	-	-

$$LOI_{polymer} = \frac{LOI_{BSC} - LOI_{soil}}{LOI_{polymer} - LOI_{soil}} \quad (1)$$

This approach follows the same principle as the component-based method described by [17]. The resulting polymer contents derived from LOI measurements and Equation (1) are presented in Fig. 7. When evaluating the initial polymer concentrations, it becomes evident that the applied method underestimates the polymer content by up to approximately 0.4 % g polymer/g BSC, depending on the CMC type. This discrepancy between the actual polymer content and the LOI-derived polymer content has also been reported in previous studies [17]. Nevertheless, because this systematic error affects both the initial and degraded states in a comparable manner, a relative comparison between these states remains valid. A clear reduction in polymer content after the swelling pressure tests is observed for all CMC variants. Based on LOI measurements, the polymer content of CMC-L0.9 decreases by approximately 36%, while CMC-S0.9 shows a reduction of about 41%. The strongest decrease is observed for CMC-S1.2, where the LOI-derived polymer content is reduced by approximately 55%, corresponding to more than a halving of the initial value. This pronounced decrease can be attributed to polymer degradation processes, likely involving biodegradation, as well as potential polymer leaching during the testing period.

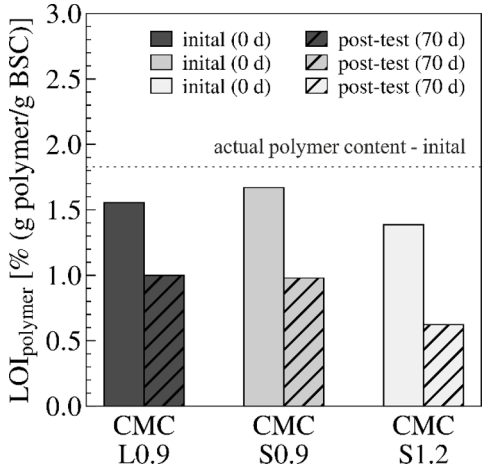

Fig. 7. Polymer content based on LOI measurements for all CMC-modified samples in the initial and post-test state.

By redispersion and centrifugation of the BSC the distribution of polymer between the soil-bound fraction (sediment) and the free fraction within the pore space (supernatant) was assessed. For each sample, the polymer content in the sediment and supernatant was calculated based on the mass fractions of wet and dry material and on LOI measurements, following Equation (1). The resulting polymer mass fractions, normalised by the total polymer content in the sample, are presented in Fig. 8. In both the initial and post-test states, the fraction of polymer associated with the sediment decreases systematically from CMC-L0.9 to CMC-S1.2. For CMC-S0.9, no sediment-bound polymer could be quantified based on LOI measurements; instead, negative values were obtained (–1.7 % g polymer/g BSC initially and –1.0 % g polymer/g BSC after testing). This behaviour reflects the previously identified underestimation of polymer content derived from LOI (Fig. 7) and indicates a systematic bias of the applied method. Nevertheless, the results clearly indicate that, in contrast to CMC-L0.9 and CMC-S0.9, CMC-S1.2 exhibits no or only a negligible degree of soil-bound polymer fraction.

In the post-test state a pronounced decrease in total polymer content was observed for all variants (Fig. 7). However, for CMC with DS = 0.9, the relative fraction of soil-bound polymer increased markedly (Fig. 8). For CMC-L0.9, the soil-bound polymer fraction increased from 20.8% in the initial state to 48.8% after testing, while for CMC-S0.9 it increased from 15.1% to 27.1%. This shift indicates preferential degradation or loss of free polymer in the pore space, whereas soil-bound polymer is retained to a greater extent. Importantly, for both CMC-L0.9 and CMC-S0.9, not only the relative but also the absolute amount of polymer retained in the sediment (soil-bound) increased after testing compared to the initial state. This finding indicates progressive polymer-soil interactions

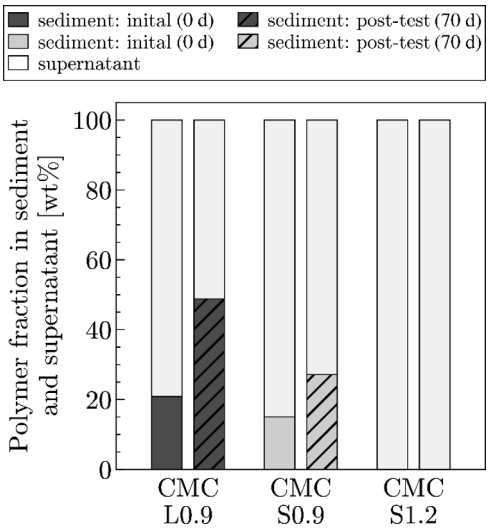

Fig. 8. Fraction of the polymer in the sediment (soil-bound) and the supernatant (free) for the initial and post-test state after redispersion and centrifugation.

during long-term exposure under hydromechanical loading. Such time-dependent strengthening of polymer-soil bonding is consistent with enhanced mechanical coupling, which has been shown to contribute to increasing unconfined compressive

strength in polymer-modified soils during curing stages [26].

In addition to LOI measurements, the rheological properties of the supernatant were analysed to investigate possible degradation processes of the free polymer fraction within the pore space. For that purpose, the viscosity-shear rate relationship was determined. The measured viscosity, particularly at low shear rates, is highly sensitive to polymer concentration and molecular chain length [27]. Higher polymer concentrations and longer polymer chains result in increased viscosity. Fig. 9 shows the viscosity-shear rate relationships of the supernatants for all CMC-modified variants in both the initial and post-test states.

All CMC supernatants exhibit the characteristic shear-thinning behavior typical of linear, water-soluble polymers. In the initial state, CMC-L0.9 shows a markedly higher viscosity at low shear rates compared to the shorter-chain CMC-S0.9 and CMC-S1.2, which display nearly identical viscosity curves, reflecting differences in molecular chain length. In the post-test state, all supernatants exhibit substantially reduced viscosities and a less pronounced shear-thinning response, indicating a reduction in effective chain length, consistent with polymer chain scission over time.

While LOI-based analysis indicates the highest total polymer loss for CMC-S1.2, rheological measurements show that this variant retains viscosity characteristics closest to its initial state, indicating comparatively limited structural degradation of the free polymer fraction. This observation is consistent with previous studies reporting reduced biodegradation of CMC with increasing degree of substitution [19]. In contrast, CMC-L0.9 exhibits the most pronounced changes in rheological behavior, reflecting a substantial reduction in molecular chain length. These results demonstrate that polymer mass loss and structural degradation do not necessarily occur to the same extent.

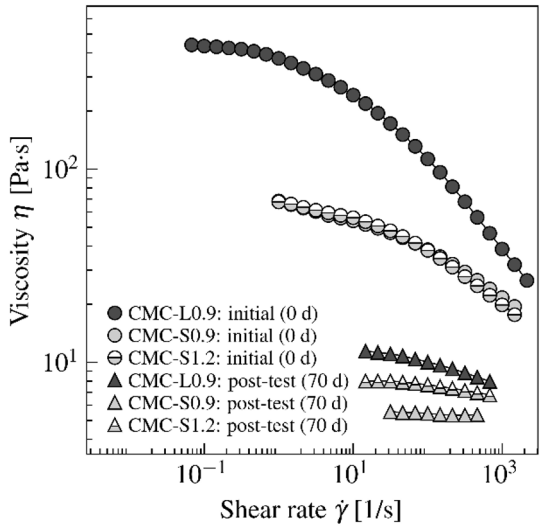

Fig. 9. Viscosity-shear rate relationship of the supernatants (free polymers) for the initial and post-test state after redispersion and centrifugation.

4 Conclusion

The mechanical response of CMC-modified loam under constant-volume conditions during saturation was governed by the saturation-dependent behaviour of the polymer phase. Stress evolution was found to be closely related to the increasingly ductile response of CMC upon wetting and to osmotic effects, which likely promoted enhanced water uptake and volumetric expansion of the soil-polymer system.

The long-chain CMC-L0.9 consistently generated the lowest total stresses over time, whereas the CMC variant with the higher degree of substitution CMC-S01.2 exhibited the highest peak stresses. Although pure CMC-L0.9 shows a higher intrinsic stiffness (Fig. 5) and higher initial supernatant viscosities (Fig. 8), these properties cannot be fully mobilised under geotechnical boundary conditions. Due to its reduced compactability, the polymer is likely displaced into the pore space during saturation, thereby limiting its ability to contribute effectively to stress transfer within the soil skeleton.

Based on mass balance considerations, CMC-S1.2 exhibited the highest apparent degree of degradation (Fig. 7). This can be attributed to the comparatively small soil-bound fraction of CMC-S1.2, which shows greater resistance to degradation processes (Fig. 8). However, rheological analyses indicate that the free polymer chains of CMC-S1.2 are more resistant to biological degradation than those of CMC-S0.9 and CMC-L0.9 (Fig. 9). Consequently, the molecular structure of the CMC-S1.2 in the supernatant remains largely intact during saturation.

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