

# Natural soil stabilized with ionic crosslinked xanthan gum and cellulose nanofiber for sustainable rammed earth construction

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**ABSTRACT:** Rammed earth (RE) is a proven sustainable construction technique, yet its widespread application is limited by the inherent mechanical constraints of earth, such as low strength and stiffness. This study explores innovative bio-inspired treatments to enhance RE materials, shifting away from the traditional, non-ecofriendly chemical-based stabilization that uses cement or lime. In this case, novel cellulose nanofiber (CNF), pure xanthan gum (XG), and modified xanthan gum based on ionic crosslinking with trivalent chromium (III) salt ( $\text{Cr}^{3+}$ -XG) were blended with natural soil in different amounts (0.5%, 1.0%, and 1.5% by weight of dry soil) to produce CNF-treated soil (CNFS), XG-treated soil (XGS), and  $\text{Cr}^{3+}$ -XG treated soil (CXS). Unamended rammed earth soil (URE) served as the control. A comprehensive experimental study was conducted to understand the effects of different bio-treatments on soil consistency, compaction characteristics, unconfined compressive strength (UCS), and chord elastic modulus. Scanning electron microscopy further examined the microstructural changes contributing to strength development. Results indicated that increasing treatment levels led to increased liquid and plastic limits while altering the fine grain soil classification from low plasticity to higher plasticity categories. The optimum water content and maximum dry density of the treated samples followed an increasing and decreasing trend, respectively, with increasing bio-additive amount, and the results were within ranges typically quoted for rammed earth. The interactions between the biopolymers and soil positively influenced strength and stiffness. Notably, an optimal concentration of 1.5% improved UCS by more than 100% for XGS and CXS, and approximately by 62% for CNFS post 28-day drying. This research underscores the promising potential of bio-treatments for sustainable engineering and promotes innovative material use in RE construction. Furthermore, the ionic crosslinking of XG with trivalent salts could be a viable strategy for reducing the biodegradability of XG, thereby enhancing its long-term stability in earthen structures.

**KEYWORDS:** Natural soil, bio-based materials, xanthan gum, cellulose nanofiber, mechanical properties.

## 1 INTRODUCTION

Rammed earth (RE) has a rich historical heritage that traces back to semi-nomadic societies in the Middle East, existing even before the introduction of mud brick, and has been utilized in iconic structures such as the Great Wall of China and other ancient monuments (Pacheco-Torgal and Jalali, 2012). The appealing combination of RE's structural integrity, enhanced indoor air quality, minimal carbon emissions, cost-effectiveness, low energy consumption, reduced use of non-renewable resources, and limited waste generation (Khadka, 2020) makes it an attractive choice for sustainable building practices today. In general, the RE construction technique involves compacting natural soil comprising of gravel, sand, silt and clay into layers within a temporary formwork, followed by a drying phase to increase strength (Minke, 2006). Small amounts of stabilizers (usually 5 to 10% by weight) can be added to the RE mix for enhancing its mechanical properties. In this case, the most frequently used stabilizers are chemical-based additives like cement and lime, as well as petroleum-based alternatives such as bitumen. Although these aforementioned stabilizers are effective for improving mechanical performance, their high carbon footprint undermines the environmental benefits of rammed earth.

Consequently, biopolymer materials such as xanthan gum (XG), guar gum, tung oil, tannin, animal glue, and lignosulfonate have emerged as potential ecofriendly stabilizers for rammed earth (Losini et al., 2022; Lin et al., 2021; Toufigh and Kianfar, 2019; Muguda et al., 2022; Abdelaal et al., 2025; Sesay et al., 2025). In this category, xanthan gum has attracted the most interest among researchers, thanks to its exceptional temperature and pH stability, as well as its lower cost and ease of use compared to other biopolymers (García-Ochoa et al., 2000). However, there are some physicochemical challenges in utilizing XG on an industrial scale, such as its susceptibility to microbial degradation, its hydrophilic nature owing to polar moieties and water-soluble characteristics, and its tendency to display weak gel-like properties due to the weak ionic bonds between its intertwined molecular chains (Lee et al., 2022; Soldo et al., 2020). Still, the presence of responsive functional

groups within the molecular structure of XG allows for modifications through physical, chemical, genetic, or enzymatic methods to address these weaknesses and expand the material's practical applications (Kashaudhan et al., 2024). Specifically, chemical modifications made by crosslinking XG with metal ions have shown positive outcomes in geotechnical applications, resulting in enhanced wet mechanical strength of silty sand and lean clay (Lee et al., 2023b), increased bearing capacity and lower hydraulic conductivity of sand (Lee et al., 2023c), and improved soil penetration resistance of sand (Rahbari et al., 2017). Although the studies on this subject are quite few and mostly conducted for cohesionless sand, they unlock a significant research area that involves the application of ionically crosslinked XG in geotechnical engineering. Therefore, the present study is an attempt to use chemically modified XG based on ionic crosslinking with trivalent chromium ( $\text{Cr}^{3+}$ ) for RE stabilization. It is known that XG can effectively form ionic crosslinks with trivalent cations than with divalent or monovalent variants, especially across a broader pH spectrum (Lee et al., 2023c; Rahbari et al., 2017; Lee et al., 2023a; Yadav et al.). Moreover,  $\text{Cr}^{3+}$  is recognized for its high competitiveness in forming homogeneous gels due to its reactivity across a wide pH range, its commercial popularity (Marudova-Zsivanovits et al., 2007) and adaptability regarding gelling time (Lee et al., 2023c), hence, its selection for this study.

In addition to the foregoing, the attractiveness and competitiveness of bio-stabilized rammed earth (BRE) technology can be further improved by exploring new and innovative materials for stabilizing rammed earth (Sesay et al., 2025). Therefore, this study also investigated cellulose nanofiber (CNF), a new generation biopolymer, to assess its potential to improve the geotechnical and mechanical properties of rammed earth. CNF is the result of ongoing innovations that utilize agricultural products, by-products, and biomass as raw materials. Currently, CNF has applications across various sectors, including cosmetics, automotive, paint, optical films, and biomedicine (Das and Bhattacharyya, 2015). However, there is a dearth of documentation regarding its usage as a soil

treatment agent. One study indicated that CNF could enhance soil stability for agricultural purposes by reinforcing critical bonds for aggregate formation (Ngo et al., 2024). Others proposed CNF as a supplementary material for cement-treated soft soils (Takahashi et al., 2021) and as additives for earth plasters (Gallo Stampino et al., 2023). Although these studies suggest that CNF improves soil performance, its effectiveness and strengthening mechanism can vary from soil type to soil type due to differences in soil texture, organic content, and other properties. In the case of earthen materials composed of gravel, sand, silt and clay, this variability may contribute to a limited understanding of the complex relationship between CNF and the natural soil matrix, potentially limiting its wider application as a soil enhancer. Therefore, this research aims to explore, for the first time, the use of CNF as a bio-based soil stabilizer, with a focus on its effects on plasticity, compaction, and compressive mechanical properties.

## 2 MATERIALS AND METHODS

### 2.1 Base soil

Soil sourced from a construction site in Canberra, Australia was utilized as the base material for this study. The soil was screened and then passed through a 19 mm sieve to eliminate larger aggregates. Its basic index properties, including grain size distribution, liquid and plastic limits, organic matter content, specific gravity (Gs), maximum dry density (MDD), and optimum water content (OWC), were determined, as shown in Table 1. Based on the Unified Soils Classification System (USCS), the soil is categorized as clayey sand (SC).

Table 1. Physical properties of base soil.

Index property	Value	Unit
<i>Grain size distribution</i>		
Gravel content (> 2 mm),	21	
Sand content (0.06 – 2 mm)	31.6	%
Silt content (0.002 – 0.06 mm)	42.1	
Clay content (< 0.002 mm)	5	
<i>Atterberg limits</i>		
Liquid limit	35.7	
Plastic limit	16.5	%
Plasticity index	19.2	
Organic matter	<1	%
Specific gravity (Gs)	2.58	-
MDD	1.98	g/cm <sup>3</sup>
OWC	10.3	%
USCS classification	SC	

### 2.2 Biopolymers and ionic crosslinking reagents

This study uses two commercially available biopolymers for the stabilization of RE, namely cellulose nanofiber (CNF) and xanthan gum (XG). The source of Cr<sup>3+</sup> for the ionic crosslinking of XG was chromium (III) nitrate nonahydrate [Cr(NO<sub>3</sub>)<sub>3</sub>.9H<sub>2</sub>O]. Additionally, a 0.05M NaCl solution was incorporated to enhance the crosslinking reaction between XG and Cr<sup>3+</sup> (Rochefort and Middleman, 1987). Both Cr(NO<sub>3</sub>)<sub>3</sub>.9H<sub>2</sub>O and NaCl were acquired as analytical-grade salts.

### 2.3 Sample preparation

The biopolymer concentration in this study was maintained at 0.5%, 1.0%, and 1.5% by weight of dry soil (wt%). Different methods were utilized in formulating the BRE mixtures with the various biopolymer materials. The CNF-treated soil (CNFS) was prepared by blending dry CNF powder with the base soil and subsequently adding the required amount of deionized water (DW). The XG stabilized soil (XGS) and Cr<sup>3+</sup>-XG stabilized soil (CXS) were prepared as follows:

hydrogels of pure XG and of Cr<sup>3+</sup>-XG (CX) were first prepared by dissolving the specified amounts of dry XG powder in DW and in the crosslinking solution, respectively. The crosslinking solution was prepared at room temperature by dissolving tiny amounts of Cr(NO<sub>3</sub>)<sub>3</sub>.9H<sub>2</sub>O salt (15% by weight of dry XG) along with 0.05M NaCl in DW. Due to the thickening properties of XG at low concentrations, it was challenging to use a laboratory mixer to produce the XG and CX hydrogels. Consequently, a commercial food processor was employed, and the mixing was carried out for 1 minute at a speed of 20,000 rpm. The pH of the CX solution was measured at 3.75, which lies within the typical pH range (2 - 7) necessary to form stable CX crosslinks (Shibaev et al., 2020). The prepared XG and CX hydrogels were then thoroughly mixed with the dry soil to achieve uniform XGS and CXS mixtures.

### 2.4 Atterberg limits tests

Atterberg limits tests were conducted following ASTM D4318 (2017) guidelines to determine the liquid limit (LL), plastic limit (PL), and plasticity index (PI) of the URE and BRE samples. Accordingly, the LL was measured using the Casagrande cup method, while the PL was determined by rolling a 3.2 mm diameter thread until it began to crumble. The PI for the samples was calculated as LL – PL.

### 2.5 Modified Proctor Compaction test

The modified Proctor compaction (MPC) method was adopted in this study to determine the compaction properties of both treated and untreated soil samples, as it closely reflects an actual on-site RE compaction (Burroughs, 2010; Maniatidis and Walker, 2003). According to the MPC method (ASTM D1557, 2021), the prepared soil mix was compacted in five layers by dropping a 4.5 kg rammer from a height of 457 mm. The number of blows per layer required to achieve the modified compaction effort of 2703 kN-m/m<sup>3</sup> was calculated using Equation 1.

$$E = \frac{B \times L \times W_h \times D_h}{V_m} \quad (1)$$

Where, E = compaction effort in KN-m/m<sup>3</sup>

B = Number of blows per layer

L = Number of layers

W<sub>h</sub> = Weight of hammer in Kg

D<sub>h</sub> = Height of drop of hammer in metres (m)

V<sub>m</sub> = Volume of mold in cubic metre (m<sup>3</sup>)

Based on Equation 1, samples for the OWC and MDD determination were produced in a cylindrical mold (152.4 mm diameter by 132 mm height) by applying 64 blows per layer using an automatic compaction machine. For each soil mix, five trials were carried out with the initial water contents increasing by 2% to obtain the compaction curves.

### 2.6 Unconfined compression test

Unconfined compression (UC) tests were conducted in accordance with ASTM D1633 (2017) to determine the stress-strain characteristics of both treated and untreated samples and to obtain key mechanical parameters including the unconfined compressive strength (UCS) and elastic modulus. Specimens for the UC tests were manufactured in cylindrical moulds measuring 100 mm in diameter and 200 mm in height. All samples were tested after 28 days of drying in an environmental condition of 23°C and 50% relative humidity. For every biotreatment condition, three specimens were tested at a constant strain rate of 1 mm/min (0.5%/min), and the average results were reported.

### 2.7 Microscopic analysis

Scanning electron microscopy (Zeiss UltraPlus FESEM) was performed on extruded sample fragments after UC tests to investigate the microstructural characteristics of the BRE specimens. The selected pieces were dried in an oven at 50°C

for 24h and then coated with 20 nm thick carbon layer to induce conductivity.

### 3 RESULTS AND DISCUSSION

#### 3.1 Effect of bio-based treatment on soil consistency

Liquid limit and plastic limit tests were performed on untreated and biopolymer-treated soils to determine the effect of biopolymer on soil consistency. The results that include different percentages of CNF, XG, and Cr<sup>3+</sup>-XG are shown in Figure 1.

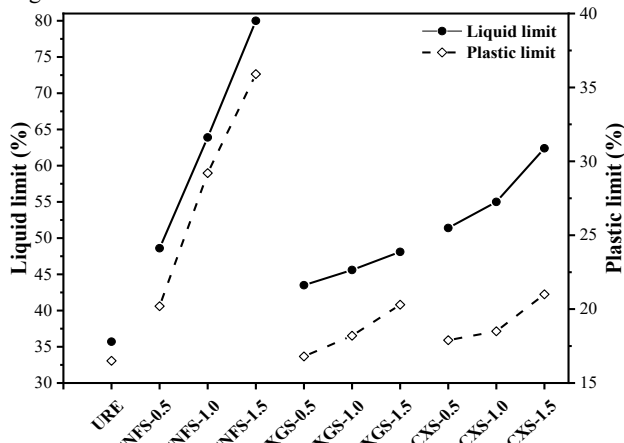


Figure 1. Variation of LL and PL with biopolymer type and amount

As illustrated in Figure 1, there was a notable rise in both LL and PL values as the application rate of biopolymer increases. The LL of the non-stabilized soil (URE) was 35.7%, rising to 80%, 48.1%, and 62.4% at 1.5% concentrations of CNF, XG, and Cr<sup>3+</sup>-XG, respectively. Likewise, the PL values showed a marked increase from 16.5% for URE to 35.9%, 20.3%, and 21% for 1.5% CNFS, XGS, and CXS, respectively. Among the various stabilized soil mixtures, CNFS demonstrated the most rapid, linear increase in both LL and PL. CNF has a strong water absorption capability due to its distinctive three-dimensional (3D) network structure (Ngo et al., 2024) and its fibrous nanoscale nature (Solhi et al., 2023). As the application rate of CNF in the soil increases, its 3D network swells, producing a greater number of hydroxyl groups that act as primary sites for water retention (Solhi et al., 2023), hence, its rapid increase in soil consistency. Similarly, the soil-biopolymer electrical interactions in the XG-based mixtures is known to enhance water holding capacity (Singh and Das, 2020) (Sulaiman et al., 2022). Specifically, this interaction can facilitate the aggregation of fine grains into a flocculated structure with more voids for retaining water (Singh and Das, 2020). It is also important to highlight that the flocculation efficiency of anionic polysaccharides can significantly increase at lower solution pH levels due to compression of the diffuse double layer of the soil particles (Theng, 2012). In this study, the pH of the biopolymer hydrogel decreased from neutrality for pure XG to an acidic level (pH = 3.75) for Cr<sup>3+</sup>-XG. Consequently, the aggregation of fine-grained soil particles in the CXS mixture was significantly greater compared to XGS at all treatment levels, leading to higher consistency for CXS than for XGS.

The impact of biopolymer stabilization on the soil's plasticity can be further understood through the Casagrande plasticity chart plotted in Figure 2.

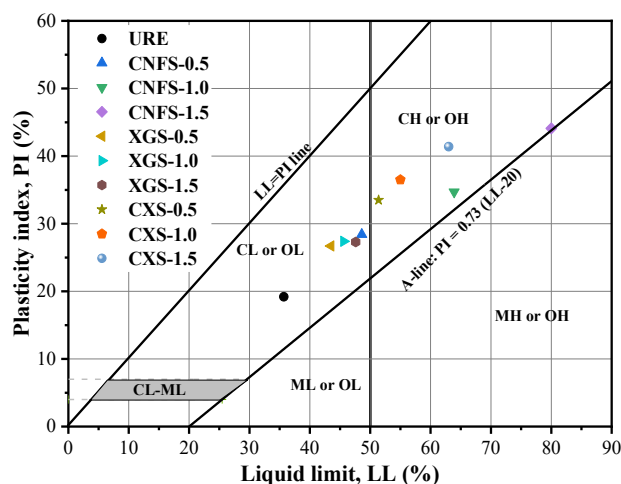


Figure 2. Casagrande's plasticity chart of treated and untreated soil mixes

According to the USCS classification (ASTM D2487, 2025), the fine fraction of the natural soil (URE) was categorized as "clay of low plasticity" (CL). However, as illustrated in Figure 2, the incorporation of biopolymers in different proportions progressively shifted the soil classification to "clay of intermediate plasticity" (CI) and "clay of high plasticity" (CH). Specifically, the addition of 0.5%, 1.0%, and 1.5% XG altered the original CL classification to CI. In contrast, for all levels of Cr<sup>3+</sup>-XG added, a direct transition from CL to CH was observed, indicating the crosslinking effect of XG on the plasticity of the soil.

#### 3.2 Compaction behavior of URE and BRE mixes

Figure 3 presents the compaction curves of the URE and BRE samples. Due to a striking similarity in the results of XGS and CXS, Figure 3 only displays the curves for XGS and CNFS for better representation.

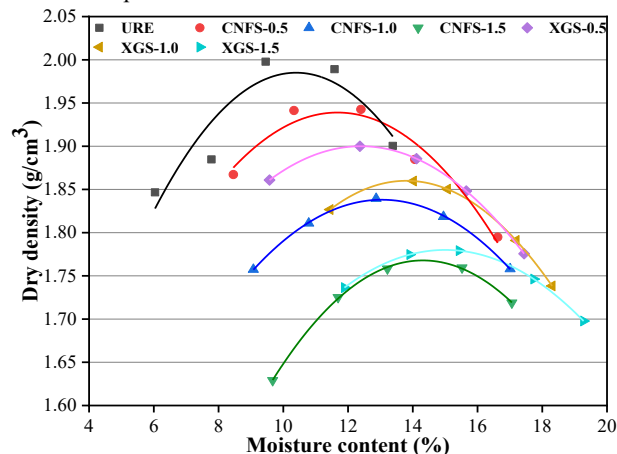


Figure 3. Compaction curves of URE and BRE mixtures

As shown in Fig. 3, the compaction curves of the BRE samples exhibit a comparatively gentler slope than URE around their respective OWC, and this trend is more pronounced with the XG-based mixtures. The tendency of the bio-based treatments to flatten the compaction curve of RE is particularly relevant in field applications where rapid moisture changes are experienced, as it indicates the potential of BRE to maintain a stable MDD over a wide range of moisture contents. The OWC and MDD of the various samples were determined from the compaction curves and the results are presented in Figure 4.

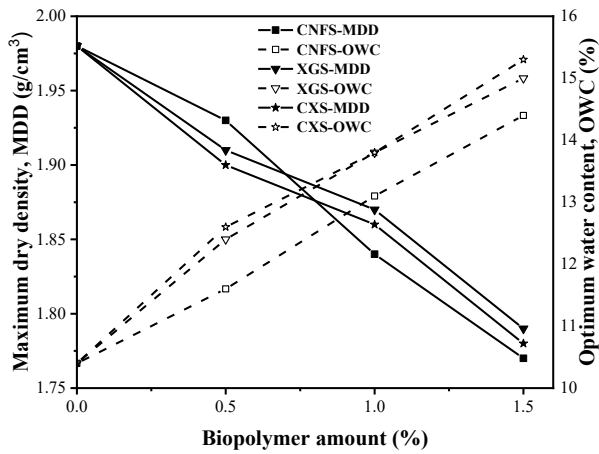


Figure 4. MDD and OWC variation with biopolymer amount

As depicted in Figure 4, the OWC of the BRE mixtures exhibits an upward trend as the biopolymer content increases, while the MDD shows a downward trend. The OWC and MDD of CNFS range between 10.3% and 14.4% and 1.98 to 1.77 g/cm<sup>3</sup>, respectively, whereas the XGS and CXS samples fall between 10.3% and 15.3% and 1.98 to 1.78 g/cm<sup>3</sup>, respectively. Adequate compaction is essential for producing a strong, stable, and durable RE structure. Although the MDD of RE is reduced after biopolymer treatment, the results are within the range of 1.7 g/cm<sup>3</sup> - 2.2 g/cm<sup>3</sup>, which are commonly reported for RE (Maniatidis and Walker, 2003; Walker, 2002). Both CNF and XG are lightweight materials having lower densities than soil grains. Therefore, their integration into the RE soil matrix can increase pore volume and reduce grain-on-grain contacts during compaction, which would eventually lead to a decrease in MDD. Similar behavior was also observed in previous studies that used other lightweight biomaterials, such as coconut coir (Raavi and Tripura, 2020), wool fibers, tannin, and lignin sulfonate (Losini et al., 2022) for RE stabilization.

Regarding the notable rise in OWC after bio-treatment, this can be attributed to the high water-absorption capabilities and pore-filling effects of both XG and CNF. Given a set pore size, an increase in the concentration of XG can lead to higher swelling capacity of the hydrogel and increased viscosity (Gales et al., 1994). Consequently, the amount of easily mobile water molecules inside the soil structure would be limited (Chang et al., 2016), thereby raising the OWC. Within the CXS mixture, improved crosslinking systems between Cr<sup>3+</sup> and the carboxylate groups of XG can lead to a more compact network and smaller micropores in the Cr<sup>3+</sup>-XG hydrogel (Park and Kim, 2010). As a result, additional movement restrictions are further placed on the trapped water molecules, which could explain the slightly higher OWC of CXS than XGS (Figure 4). CNF, on the other hand, possesses both hydrophilic and nanoscale properties. Therefore, as the concentration of CNF in the soil matrix increases, more surface area for water contact becomes available (Ngo et al., 2024), which subsequently raises the OWC. However, when compared with the XG-based samples, the OWC of CNFS remains lower across all treatment levels, possibly due to more water required for XGS and CXS to form their respective high viscous hydrogels (Sulaiman et al., 2022; Singh and Das, 2020).

### 3.3 Unconfined compression test results

The stress-strain curves for the URE and BRE mixtures at various biotreatment levels are presented in Figure 5.

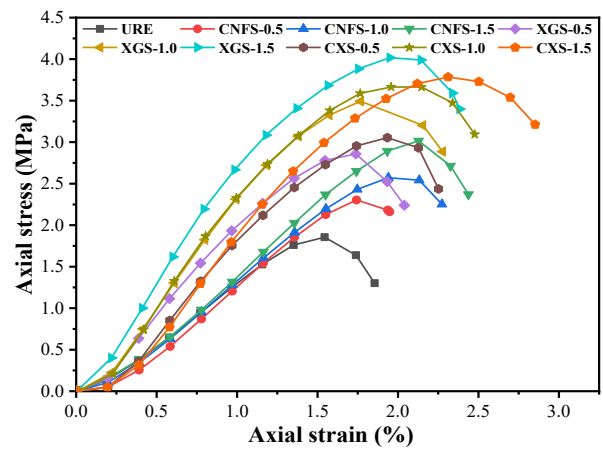


Figure 5. Stress-strain curves of URE and BRE mixtures

As shown in Figure 5, the peaks of the stress-strain curves of the BRE samples lie to the upper right of the URE curve, indicating that CNF, XG, and Cr<sup>3+</sup>-XG generally enhance the stress and strain capacity of RE. At 0.5% and 1.0% concentrations, CXS recorded the highest peak stress and peak strain, followed by XGS and CNFS respectively. However, when the biopolymer concentration was raised to 1.5%, the peak stress of CXS slightly fell below XGS. The unconfined compressive strength (UCS) and the strength improvement ratio,  $SIR = \frac{S_t - S_u}{S_u} \times 100\%$  (where,  $S_t$  is the strength of treated sample and  $S_u$  is the strength of untreated sample) were obtained for all samples and used to compare their performance effectiveness. The results are reported in Figure 6.

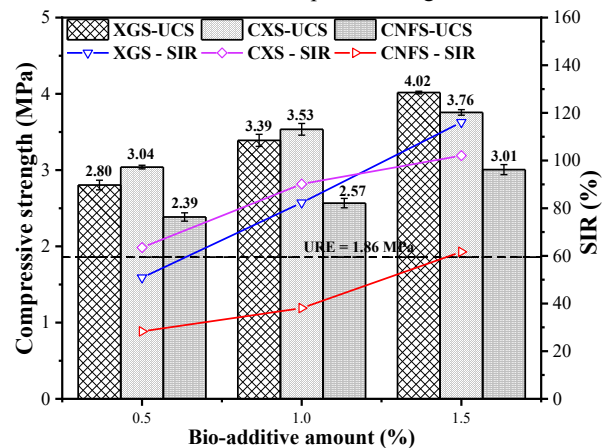


Figure 6. Effect of bio-treatment type and amount on UCS

As illustrated in Figure 6, the BRE mixtures showed considerable improvements in UCS compared to the URE control sample, which has a UCS of 1.86 MPa. Some relevant guidelines (CSIRO, 1987; New Mexico Earthen Building Materials Code, 2021; SADC ZW HS 983, 2014) recommend a minimum compressive strength of 2 MPa for load bearing rammed earth. As can be seen in Figure 6, this requirement was adequately met after bio-treatment. Specifically, soil stabilized with 0.5% CNF, XG, and Cr<sup>3+</sup>-XG achieved a UCS of 2.39 MPa, 2.80 MPa, and 3.04 MPa, respectively. As expected, a further increase in bio-treatment concentration led to a corresponding increase in UCS. Therefore, the maximum UCS was obtained at 1.5% concentration for all samples, which was the optimum inclusion level. Based on the results in Figure 6, CXS has the strongest effect on UCS at lower concentrations, recording an SIR of about 63.5% at 0.5% concentration and 90.2% at 1.0% concentration. However, at 1.5% treatment level, the SIR for XGS was the greatest, suggesting that the

ionic crosslinking effect of XG on RE strength was only predominant at lower bio-treatment levels.

The elastic modulus serves as another essential mechanical performance metric that characterizes the elastoplastic mechanical behavior of rammed earth. In this study, the elastic modulus was calculated from the stress-strain curves as the slope of the chord drawn between one-third and two-thirds of the peak stress, according to Rodríguez-Mariscal et al. (2018), and referred to as the chord modulus ( $E_c$ ). Within this range, the stress-strain curves exhibit an almost linear trend, providing a viable estimate of the material's stiffness. The results summarized in Table 2 are the average of three samples and their corresponding coefficient of variation (CoV).

Table 2. Chord modulus results

Mix	$E_c$ (MPa)	CoV (%)
URE	146.8	7.7
CNFS-0.5	165.4	3.6
CNFS-1.0	173.3	2.1
CNFS-1.5	190.1	3.0
XGS-0.5	228.7	7.9
XGS-1.0	259.1	3.6
XGS-1.5	267.1	4.4
CXS-0.5	215.6	1.7
CXS-1.0	245.5	5.7
CXS-1.5	246.1	3.0

The  $E_c$  of the BRE samples are significantly higher than that of URE, as shown in Table 2, suggesting a stiffer RE mix after biotreatment. The addition of CNF at 0.5%, 1.0%, and 1.5% concentrations, raised the  $E_c$  from 146.78 MPa for URE to 165.4 MPa, 173.3 MPa, and 190 MPa, respectively. The  $E_c$  of XGS and CXS samples ranged from 215.6 MPa to 267.1 MPa, which is significantly higher than CNFS and consistent with the UCS results. But for XGS and CXS, the impact of raising the bio-treatment concentration seems to be only noticeable at 0.5% and 1.0%. Above 1.0%, XGS and CXS did not exhibit any discernible additional increase in  $E_c$ . On the other hand, the CNF sample consistently showed an increase in  $E_c$  with the increase in treatment amount.

### 3.4 Scanning electron microscopy

SEM images were taken of the URE and the BRE specimens at the optimum 1.5% treatment dosage and shown in Figure 7.

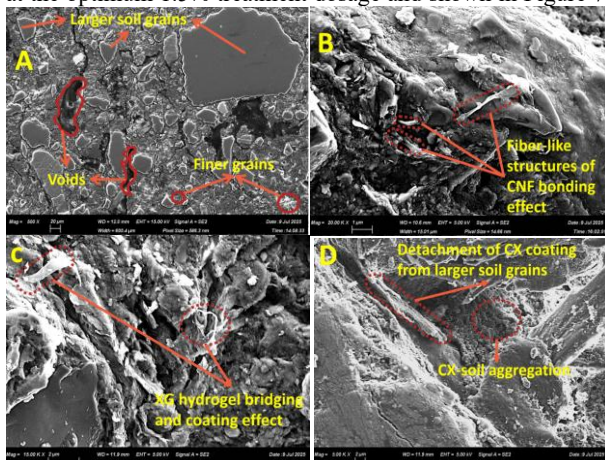


Figure 7. SEM images of treated and untreated RE mixes: (a) URE (b) CNFS (c) XGS (d) CXS

In Figure 7a, a mix of larger and irregular soil grains surrounded by finer particles and some voids can be seen for the URE sample. However, after bio-stabilization and drying, different

soil-biopolymer matrix can be observed depending on the bio-treatment type. In the case of CNFS (Figure 7b), the formation of fibre-like linkages in the pore spaces created a cementitious/binding effect that resulted in the strengthening of the BRE mix. The rough and porous structure could be an indication of the high surface area and water-retention capacity of CNF (Ngo et al., 2024). Samples treated with XG exhibited a combination of surface coating and inter-particle bridging as mechanisms for strength enhancement (Figure 7c), which is in line with the observations from previous studies (Chang et al., 2016; Chen et al., 2019). Chen et al. (2019) related the surface coating and inter-particle binding effect of XG hydrogel to its viscous property, and further noted that this contributed to better adhesion, cohesion and strengthening of the soil-biopolymer matrix. After the introduction of  $Cr^{3+}$  crosslinks, the viscous XG solution changes to a viscoelastic solid (Nolte et al., 1992) that forms a highly condensed film around the soil grains. However, it is known that CX hydrogel contracts upon drying due to changes in the ionization state of the polymer network (Gales et al., 1994; Lee et al., 2023a), which may have led to a separation of the CX coating from the larger soil grains (Figure 7d). Nonetheless, it can be confirmed that the strength development in the CXS sample is closely related to the interaction of the CX hydrogel with the finer grains to form a flocculated structure in the pore spaces.

## 4 CONCLUSIONS

In this study, the bio-based stabilization of RE with CNF, XG, and  $Cr^{3+}$ -XG was experimentally examined through modified proctor compaction tests, Atterberg limit tests, unconfined compression strength tests, and SEM analysis. CNF demonstrated a positive effect on the strength and stiffness properties of rammed earth, but the most favorable results were achieved with the XG-based samples. The UCS values obtained surpassed 2 MPa across all treatment levels, which meets the minimum requirement set by certain guidelines for rammed earth structural applications. SEM images showed the formation of fiber-like linkages of CNF producing a bonding effect in the soil mix. On the other hand, XG exhibited a surface coating and inter-particle binding effect as its strength improvement mechanism, while for CXS, the aggregation of fine grains contributed to strength development. Additional experiments will be carried out to further explore the effects of varying the initial moisture contents and curing durations on the mechanical performance of BRE, reinforcing the viability of these eco-friendly solutions in RE construction. Future studies will also investigate the possibility of drying shrinkage and potential cracking in the BRE mixes, especially for CXS where the CX gel likely experienced contraction upon drying – a phenomenon known as syneresis. Overall, this research indicates that the selected bio-treatment options could be used as potential substitutes for the traditional chemical-based stabilizers, which are known to have high carbon footprints. Besides, introducing metal ions in protective salt forms for the crosslinking of xanthan gum can increase soil salinity which may potentially reduce microbial activity and prevent biodegradation over time. Lastly, the use of nanotechnology and resulting nano products like cellulose nanofiber could enhance the market demand for its product development while adding value and additional functionality to the construction sector.

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