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Article

An Investigation on the Potential of Cellulose for Soil Stabilization

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Abstract: The construction industry remains a significant contributor to global carbon emissions. Several sustainable alternatives have emerged to overcome this issue in geotechnical engineering. In this study, cellulose, an abundant biopolymer, is investigated for its potential to modify geotechnical properties favourably. Sodium carboxymethyl cellulose (NaCMC) is an anionic ether derivative of natural cellulose with good binding and moisture-retaining capacity. Experimental investigations were conducted on organic silt stabilized with 0.25% to 1.00% NaCMC, and the results indicate that unconfined compression strength (UCS) increased by 76.7% with 0.5% NaCMC treated soil after 28 days. Hydraulic conductivity (HC) of the 0.5% NaCMC treated soil decreased by 91.7% after 28 days, and the additives suppressed the compression index of the soil by 50%. The California bearing ratio (CBR) test indicated that the additive improved the subgrade strength by 33.2%, improving it from very poor to a fair sub-grade material. Microstructural analysis using a scanning electron microscope (SEM) and chemical investigation using x-ray diffraction (XRD) indicates that NaCMC's interaction with soil did not form any new chemical compounds. However, the viscous nature of the material formed fibrous threads that bind the soil to enhance the geotechnical properties, establishing itself as a prominent stabilizer for ground improvement applications.

Keywords: cellulose; organic silt; unconfined compression strength; hydraulic conductivity; California bearing ratio

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1. Introduction

The term "ground improvement techniques" refers to the methods used to strengthen weak soil to withstand the potential structural load. Although technical interpretations of soil evolved only during the end of the 18th century with the understanding of the soil mechanics concepts; ground improvement like lime stabilization [1], fibre reinforcement with straw [2], etc., dates back to ancient periods. Since the beginning of 20th century, soil–cement mixtures have been used to strengthen pavement surfaces [3]. Chemical soil stabilization gradually gained significance as these chemicals reacted with the soil to produce a firm base for the foundation. Furthermore, these chemical stabilizers improved other engineering qualities such as hydraulic conductivity (HC) and consolidation [4]. However, manufacturing cement and lime is associated with environmental issues like carbon dioxide emission, air pollution, greenhouse effect, climate change, etc. [5].

Researchers have developed several promising techniques to substitute conventional cement and lime stabilization. The alternatives include the addition of flyash [6]; reinforcing the soil with synthetic fibres [7] and natural fibres [8]; adding ashes from agricultural waste like rice husk ash [9] and groundnut shell ash [10]; mixing the soil with rock powders like limestone powder [11] and wollastonite powder [12]; and treating the soil with biological agents like microbial stabilizers [13] and biopolymers [14,15].

Among the various methods investigated, biopolymers have emerged as environmentally friendly, biodegradable and biocompatible alternatives to conventional stabilizers.

In addition to their ground improvement potential, biopolymers preserve the indigenous nature of the soil [16]. Several biopolymers such as xanthan gum [17], guar gum [18], gellan gum [19], chitosan [20] and β-glucan [21], to mention a few, showed promising results in the strength improvement of soil. Each biopolymer is sourced from a different origin and has unique properties. For instance, xanthan gum is an anionic polysaccharide from the bacterial fermentation of glucose [22], whereas chitosan is a cationic polysaccharide from the demineralization, deproteinization and deacetylation of crustacean shells [20].

Cellulose is the most abundant biopolymer on the earth, available on the wooden barks of trees and the cell walls of plants [23], and can be extracted by environmentally friendly methods from its source [24]. Carboxymethyl cellulose (CMC) is an anionic ether derivate of natural cellulose [25]. Sodium carboxymethyl cellulose (NaCMC) is a modified CMC with excellent water solubility and a wide range of commercial [25], cosmetic [26], pharmaceutical [27] and food industry [28] applications. In civil engineering, CMC can be used as organic flocculating agents [29], strength enhancers and retarders in cement mortars [30] and soil stabilizers [31].

Few investigations show the potential of cellulose derivatives for various geotechnical applications. Ma and Ma [31] amended loess with 1.5% NaCMC and reported a 1.68 times strength improvement, thus making the soil suitable for constructing low-rise structures. Ning et al. [32] reported that the addition of NaCMC improved the moisture-holding capacity of soil and enhanced water infiltration duration by 3.94 times. This caused a reduction in the HC of the soil. Abd et al. [33] showed that CMC could reduce the rate of consolidation and suppress the compression index of low plastic clay. Owji et al. [34] investigated the resistance to wind erosion on treating the soil with CMC. They showed that the addition of 0.3% CMC reduced wind erosion by 97.8% in the dry state and 75.9% in the wet state, respectively [34].

The literature review shows that limited investigation has been carried out to support the additive performance. An in-depth understanding of the geotechnical properties of NaCMC-amended soil remains inadequate, underlining the need for a thorough investigation. Moreover, the material influence on the behaviour of problematic organic soils has not been investigated. The performance of NaCMC with time (ageing) on the soil also requires more attention to ensure its sustainability. The present study attempts to investigate the ability of NaCMC to improve the unconfined compression strength (UCS) and HC of organic silt for a curing period of 0 days, 7 days, 14 days and 28 days. In addition, the effect of NaCMC on the subgrade strength and acidic-alkaline nature of the soil was studied. The study is supported by the results of the scanning electron microscope (SEM), X-ray diffraction (XRD) and Fourier transfer infrared spectroscopy (FT-IR) to understand the mechanism of NaCMC–soil interactions.

2. Materials

2.1. Soil

The soil used for this study is black organic silt from the Ariyalur district in Tamil Nadu, India (11°00′01.7″ N, 79°03′51.8″ E). The soil was dug out manually at a depth of 1 m below an excavation trench. The soil has 13.6% organic material and a moderate differential swell index of 35%. The grain size distribution plot in Figure 1 shows that the soil has more than 50% silt (75 µm to 2 µm). The unified soil classification system categorizes the soil as OL, i.e., low plastic silt with organic content. The index and physical properties of the soil are reported in Table 1.

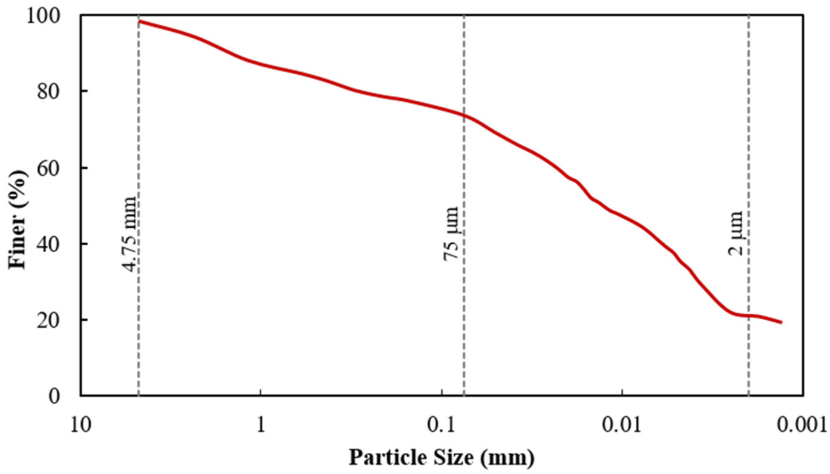


Figure 1. Grain size distribution analysis of the study soil.

Table 1. Material properties.

Material	Property	Value	Code Standard	References
Soil	Liquid limit (%)	48.8	ASTM D4318	[35]
	Plastic limit (%)	25.9	ASTM D4318	[35]
	Plasticity index (%)	22.9	ASTM D4318	[35]
	Specific gravity	2.33	ASTM D854	[36]
	Differential free swell index (%)	35	IS 2720-40	[37]
	Organic material (%)	13.6	ASTM D2974	[38]
NaCMC	Average particle size (μm)	398	-	-
	Bulk density (kg/m^3)	700	-	-
	pH of 1% solution	6	-	-
	Viscosity of 1% solution (cP)	222	-	-
	Colour	White	-	-
	Chemical formula	$C_8H_{15}NaO_8$	-	[39]
	Molecular weight (g/mol)	262.19	-	[39]

2.2. NaCMC

NaCMC is a modified form of CMC, commercially known as cellulose gum. NaCMC is a cellulose ether manufactured by alkalization and etherification of natural cellulose to get a white fibrous powder. It is an anionic and hydrophilic biopolymer that readily dissolves in hot and cold water to form a transparent viscous solution but is insoluble in organic solvents. However, the viscosity of the solution reduces with temperature. Water solubility is a typical characteristic of NaCMC, as CMC is insoluble in water. The study used commercial-grade NaCMC procured from Amster microcell Pvt. Ltd., Ambavpura, Gujarat, India. The material properties of NaCMC are listed in Table 1.

3. Methods

The excavated soil was initially air-dried for 24 h, followed by oven drying for another 24 h at 100 °C to remove the field moisture content. The soil was then rammed and sieved to varying fineness as per the requirements of the experimental investigation. The required soil for each test was divided into ten smaller equal parts. NaCMC by dry weight of the soil (0.25%, 0.50%, 0.75% and 1.00%) was added to the soil and hand-mixed thoroughly to get a uniform mixture before adding water to mix. Standard compaction effort was given to untreated and NaCMC-treated soil to determine the optimum moisture content (OMC) and maximum dry unit weight (MDU) following ASTM D698 guidelines [40]. For all the samples, the compaction test was started with an initial moisture content of 10% and raised by 2% for every trial. The compaction test was continued until a reduction in the unit weight was noticed. All the samples for further studies were prepared at their respective OMC obtained from the compaction test. The strength of the NaCMC-treated soil was estimated using the unconfined compression test and the experimental procedure was based on ASTM D2166 [41]. Cylindrical soil specimens of 38 mm diameter and 76 mm height were used for the unconfined compression test. UCS was investigated for curing periods—0 days, 7 days, 14 days and 28 days—to understand the effect of ageing on NaCMC-treated soil. Moulded soil samples were stored in moisture-lock bags until the test period. The subgrade strength of NaCMC-treated soil was investigated by conducting the California bearing ratio (CBR) test at the optimum additive dosage adhering to ASTM D1883 [42]. The CBR test verifies the suitability of the material for pavement applications. Soil blended with 0.25% to 1.00% NaCMC was continuously monitored for its HC until 28 days to understand the water infiltration behaviour of the treated soil. One dimensional consolidation test on the treated sample was carried out to understand the compressibility characteristics. The samples were loaded in stages (i.e., 0.05 kg/cm^2 (seating load), 0.1 kg/cm^2, 0.2 kg/cm^2, 0.4 kg/cm^2, 0.8 kg/cm^2, 1.6 kg/cm^2 and 3.2 kg/cm^2) followed by unloading. The HC and consolidation experiments followed ASTM D5856 and ASTM D2435 for sample preparation and test procedures [43,44].

The pH of the soil can vary from an extremely acidic to an alkaline range of 3.5 to 9 [45]. Extremely acidic soil (with pH < 4) [45] or groundwater may affect the foundation concrete, causing structural distress. A permeation model study was conducted as outlined by Kumar and Sujatha [22] to understand the soil behaviour in acidic and alkaline environments. Permeation analysis was conducted using acidic and alkaline solutions in untreated and NaCMC-treated soil (optimum dosage) media. Diluted sulfuric acid with pH 3.38 and diluted sodium hydroxide solution with pH 12 were used as acidic and alkaline solutions, respectively. The pH of the solutions before and after passing through the soil was compared for interpretation.

SEM micrographs (taken with Tescan Vega 3 SEM instrument, Brno, Czech Republic) were used to study the surface morphology of the treated samples and the mechanism of strength gain. The possible modification in the functional group was interpreted with FT-IR using a spectrometer (Perkin Elmer Spectrum One, Waltham, MA, USA). The chemical interaction between compounds in treated soil was analyzed based on the XRD patterns of a powder x-ray diffractometer (Bruker D8 focus, Billerica, MA, USA). The XRD peaks were matched based on the Joint Committee on Powder Diffraction Standards (JCPDS) database with the proprietary PCPDFWIN software. The pH variations of the acidic and alkaline solutions were measured with a pH meter (Systronics digital pH meter 335, Ahmedabad, Gujarat, India).

4. Results and Discussion

4.1. Compaction Characteristics

Optimum moisture content is the water content at which the soil attains the maximum unit weight during compaction. The organic silt soil has an OMC of 17.5% with an MDU of 16.8 kN/m^3. On adding NaCMC, OMC did not show any appreciable change (Figure 2). There was a minimal increase from 17.6% to 17.8% upon adding NaCMC from 0.25% to 1.00%. MDU of the soil reduced gradually to 14.9 kN/m^3 with 1.00% NaCMC addition to the soil (Figure 2). Adding NaCMC shifted the compaction curve slightly to the right in the downward direction.

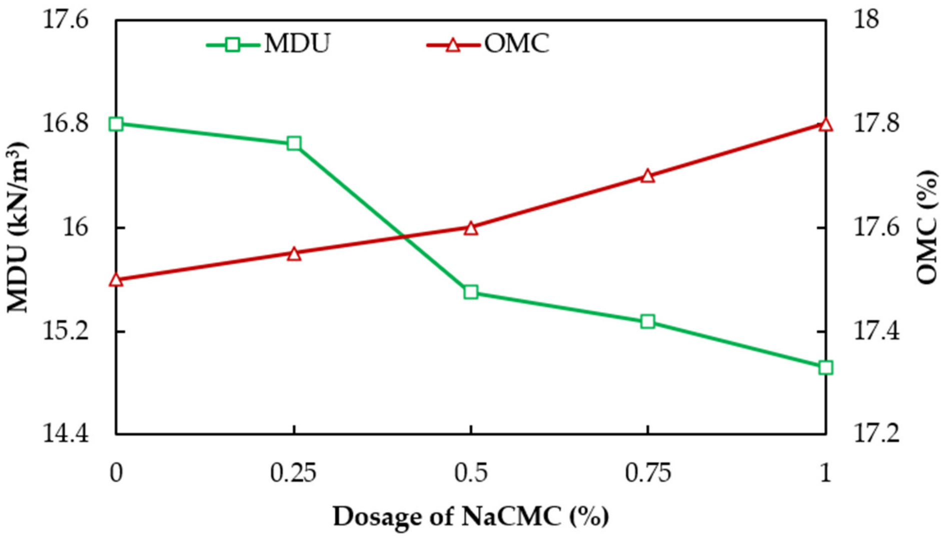


Figure 2. Variation of MDU and OMC with the dosage of NaCMC in soil.

This behaviour of marginal increase in OMC and decrease in MDU is typical of soil treated with biopolymers [31,46]. The hydrophilic nature of the additive makes the soil adsorb water, causing an increase in OMC with dosage [47]. The viscous gel fills the pore spaces and resists further compaction effort causing a reduction in the MDU. Although the soil tends to adsorb more water, excess moisture in the soil matrix would make it less dense, explaining the marginal variation in the OMC with dosage. Another plausible reason is that at higher dosages of the additive, the pore fluid is more viscous and this viscous gel prevents the particle interaction causing an increase in the void spaces, reducing the MDU [46,47].

4.2. Strength Characteristics

4.2.1. Failure Strain

Failure strain represents the maximum deformation experienced by the soil on the verge of failure. The soil has a failure strain of 4.61%. Samples treated with NaCMC experienced higher deformation than untreated soil. Failure strain decreased with an increase in dosage and ageing but always was higher than the untreated soil up to a dosage of 0.75% (Table 2). Other biopolymers like xanthan gum and guar gum showed a reduction in the failure strain on immediate testing [18,48]. This higher failure strain is a typical behaviour of NaCMC-treated soil. The NaCMC is hydrophilic, allowing water molecules to be held in the soil matrix [49], forming a viscous gel that encapsulates water for a longer period and delays drying. This renders the treated soil matrix more flexible and fails with plastic deformation compared to untreated soil.

Table 2. Failure strain of NaCMC treated soil.

Curing Period	0 Day	7 Days	14 Days	28 Days
S	4.61%	-	-	-
S + 0.25% NaCMC	6.25%	5.26%	4.93%	4.93%
S + 0.50% NaCMC	5.59%	4.93%	4.93%	3.95%
S + 0.75% NaCMC	4.93%	4.93%	4.61%	3.95%
S + 1.00% NaCMC	4.61%	4.61%	4.28%	3.95%

S—Untreated soil.

With an increase in dosage, however, the viscosity of the pore fluid increases, resulting in a stiffer soil matrix that fails at a lower strain rate than the soil treated with a lower dosage. The higher viscosity at higher dosages also deters the mobilization of cohesion between the particles, leading to failure at a lower strain rate. Another notable behaviour is that most biopolymers, with ageing, induce a brittle nature to the soil with a rapid fall of stress after failure [50]. This behaviour would cause catastrophic failure of structures built over such soils. NaCMC treatment exhibited a plastic and gradual stress–strain response after failure as observed in Figure 3, and it remains plastic even at higher curing periods. Chen et al. added polypropylene fibres to address the brittle nature of xanthan gum-treated silty clay [51]. In this regard, the choice of NaCMC is advantageous, as the treated soil exhibited plastic behaviour even at a longer curing period without any fibre reinforcement.

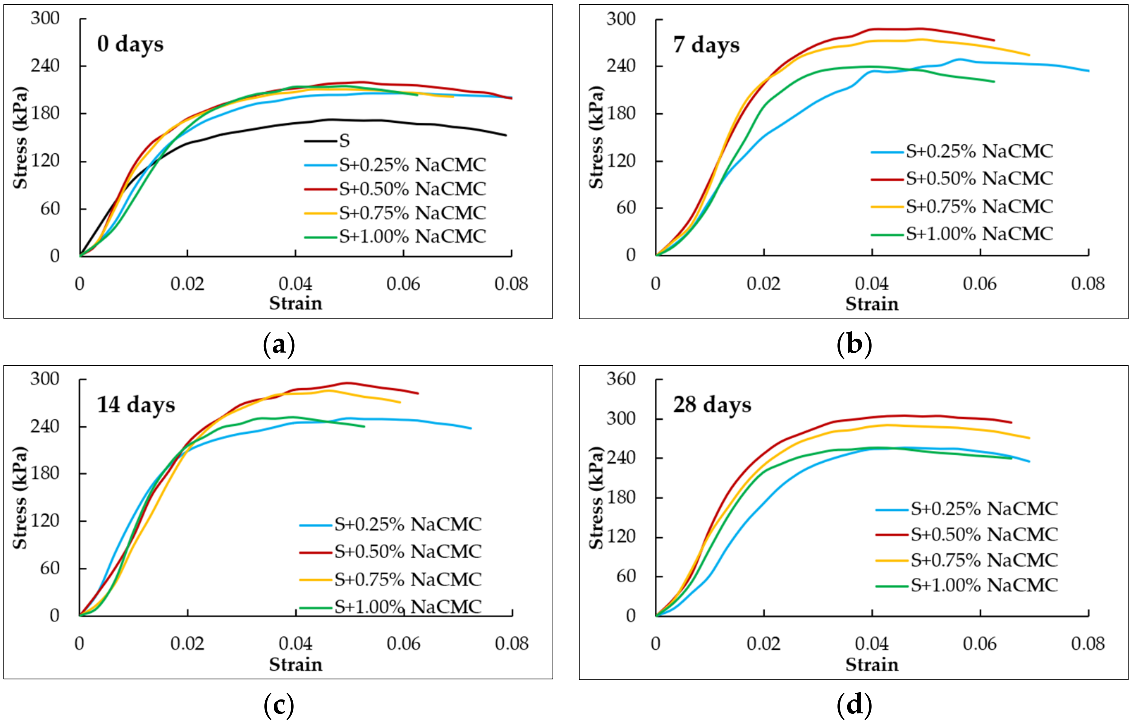


Figure 3. Stress–strain response of NaCMC treated soil at (**a**) 0 days; (**b**) 7 days; (**c**) 14 days; (**d**) 28 days.

4.2.2. UCS

Strength reflects the maximum load the soil can sustain on the verge of failure. It is an essential parameter in determining the bearing capacity of foundations. The untreated soil has a UCS of 172.4 kPa. The UCS and the percentage of strength improvement in NaCMC-treated soil is shown in Figure 4. A minimum addition of 0.25% NaCMC increased the UCS to 205.12 kPa, i.e., 19%. The results from Figure 4 show that the UCS increased up to a dosage of 0.5% and decreased at higher dosages. A constant increase in the UCS can be noticed with ageing, indicating that NaCMC tends to enhance soil strength in the long run. The UCS of 0.5% NaCMC-treated soil increased from 219.67 kPa to 304.70 kPa in 28 days. The rate of strength improvement was 27.42% during the initial (0 days) testing, which increased to 31.37% in 7 days, and further increased by almost 2.65% and 2.85% at 21 days and 28 days, respectively. This indicates that optimum curing of 7 days is required before construction on NaCMC-treated soil.

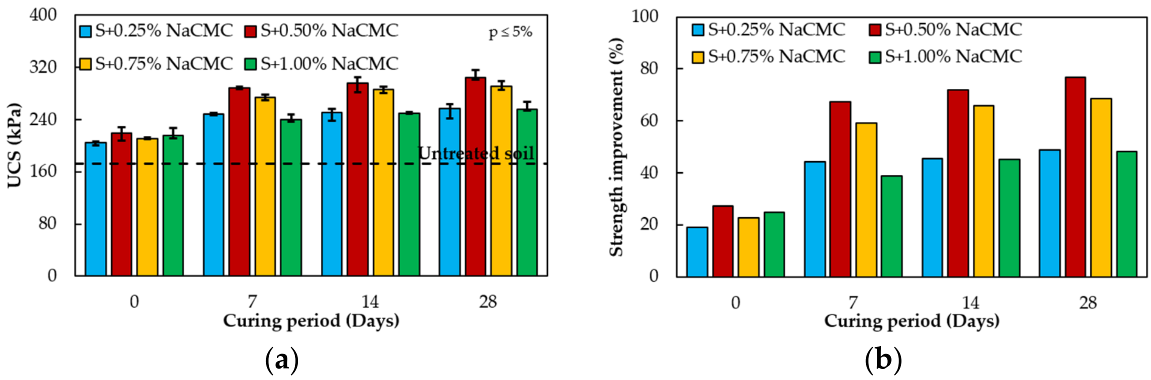


Figure 4. Strength of NaCMC treated soil (**a**) UCS at different curing periods; (**b**) Percentage of strength improvement.

4.2.3. Failure Modulus

The resistance offered by the sample to loading is determined as the ratio of strength to failure strain, known as failure modulus. The failure modulus of untreated and NaCMC-treated soil is presented in Table 3.

Table 3. Failure modulus of NaCMC treated soil.

Curing Period	0 Days	7 Days	14 Days	28 Days
S	3743.54	-	-	-
S + 0.25% NaCMC	3281.92	4173.73	4284.37	4358.55
S + 0.50% NaCMC	4445.02	5848.76	5559.75	6064.55
S + 0.75% NaCMC	5080.85	6004.00	6208.11	6340.17
S + 1.00% NaCMC	5568.63	6616.34	6793.23	6476.97

The failure modulus of 0.25% NaCMC treated soil reduced to 3281.92 kPa during the initial testing from 3743.54 kPa (untreated soil). This reduction of failure modulus is due to the higher deformation experienced by the sample as inferred from Table 2, despite the binding action of the gel. With higher dosage, due to the decreasing failure strain, the failure modulus is found to increase both with dosage and with the curing period, indicating that NaCMC can offer better resistance to failure load. A similar reduction at the initial dosage and a continuous increase of elastic modulus were observed by Ma and Ma [31] on NaCMC-treated loess.

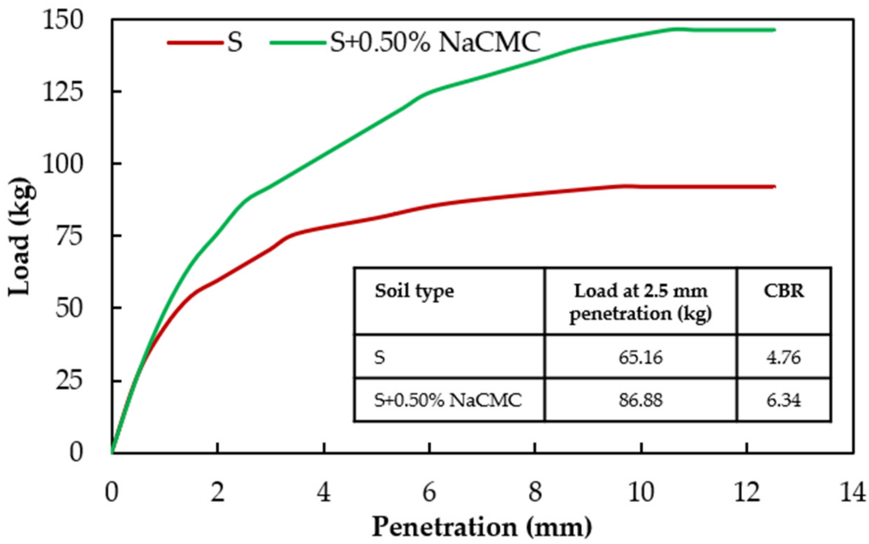
4.2.4. CBR

While UCS measures the soil's strength for geotechnical applications, the subgrade strength of the material is estimated in terms of CBR value. The CBR value of the untreated and 0.50% NaCMC (optimum dosage) treated soil was determined from the corresponding load-penetration plot as shown in Figure 5.

The CBR of untreated soil is 4.76 (based on load corresponding to 2.5 mm penetration), classifying it as a poor subgrade material. With the addition of 0.5% NaCMC, the CBR value increased by 33.19% and the soil became a fair subgrade material. Similar to UCS, additional curing of 0.5% NaCMC-treated soil would improve subgrade quality. Despite the strength improvement, adding NaCMC reduced the MDU at higher dosages. This adds another advantage of the lower soil requirement for preparing a subgrade at the same effort.

4.2.5. Strength Improvement Mechanism

Biopolymer additives may develop a variety of interactions with soil. For instance, despite being a biopolymer, chitosan improved the soil strength without forming any new chemical compounds [20]. On the other hand, Subramani et al. [52] reported that guar gum interacted with clayey sand to form calcium silicate hydrates and other cementitious products, improving the soil's potential as a better landfill liner material. Figure 6a–f represent the SEM images of untreated and 0.50% NaCMC-treated soil at 5 kx, 10 kx and 15 kx magnifications, respectively. Physically, the NaCMC formed viscous gel threads that bind the soil particles and improve strength, as observed in Figure 6.



Soil type	Load at 2.5 mm penetration (kg)	CBR
S	65.16	4.76
S+0.50% NaCMC	86.88	6.34

Figure 5. CBR of NaCMC treated soil.

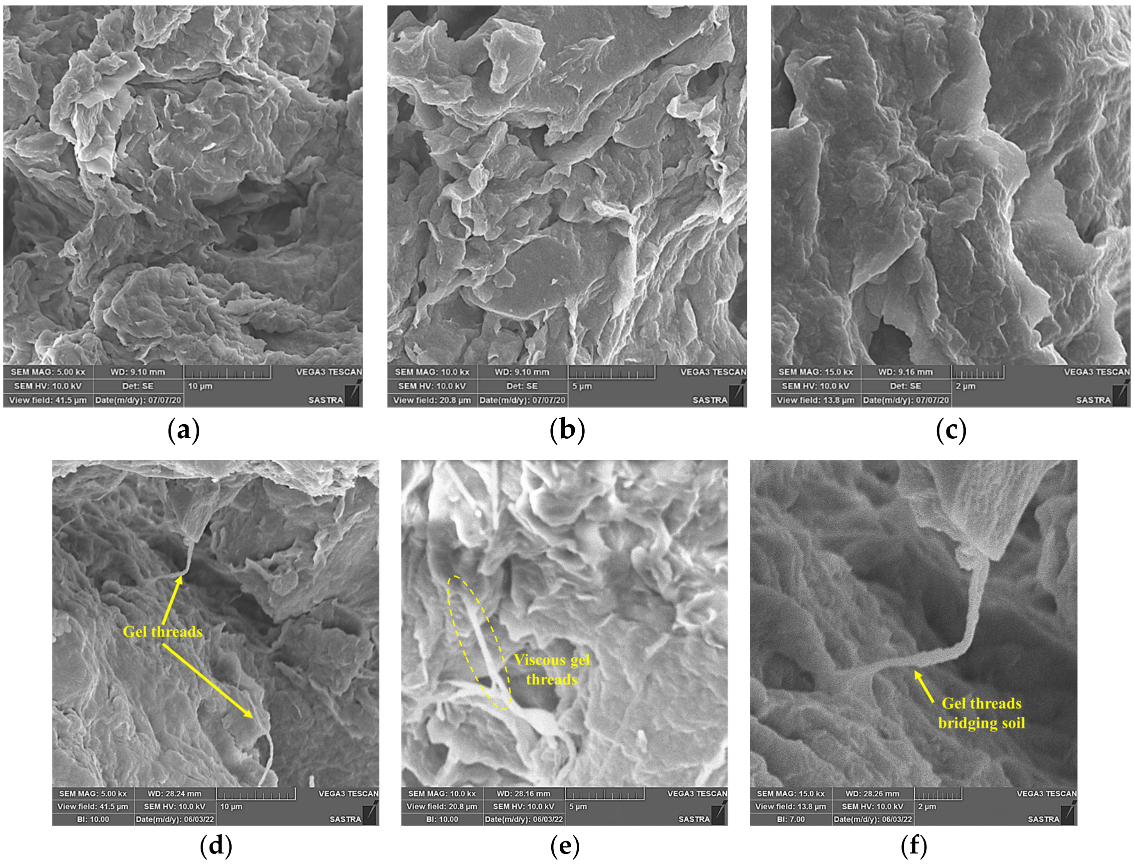


Figure 6. SEM micrographs of untreated soil at (**a**) 5 kx; (**b**) 10 kx; (**c**) 15 kx, and NaCMC treated soil at (**d**) 5 kx; (**e**) 10 kx; (**f**) 15 kx magnifications.

FT-IR analysis was conducted for wavenumber ranging between 450 cm^{-1} to 4000 cm^{-1} to study the functional group variations and to identify the potential chemical interactions between clay minerals and NaCMC. The sharp troughs around the region of 1033 cm^{-1} in Figure 7 indicate the Al-Si lattice of clay minerals [53,54] (Al—Aluminum, Si—Silicon). The peak around the 3430 cm^{-1} indicates the OH stretching of water molecules due to absorption and the peak around 1640 cm^{-1} reflects the OH bending of water molecules [53] (O—Oxygen, H—Hydrogen). The depression around 520 cm^{-1} denotes the Si-O-Al bending of clay minerals [53] and the depression around 695 cm^{-1} corresponds to the Si-O of quartz, a form of silicon dioxide [55]. The FT-IR spectra gave an idea of the clay minerals and the water absorption; however, it did not give any implication on the chemical substances formed and the chemical interaction between soil and NaCMC. Hence, XRD analysis was conducted to identify the chemical compounds.

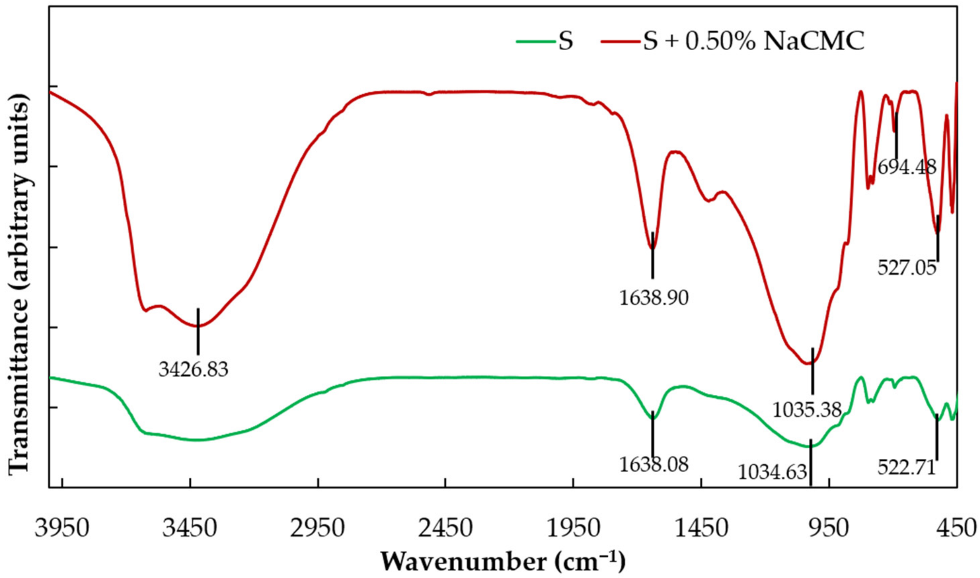


Figure 7. FT-IR spectrum of untreated and NaCMC-treated soil.

XRD analysis of soil (Figure 8) indicates the presence of silicon dioxide at peaks of 27.1° and vaterite (a polymorph of calcium carbonate) at peaks of 21.1°, 51.1° and 68.7°. Clay minerals like piezotite, halloysite and saponite were found at 40.1°, 60.3° and 28.5°, respectively. The XRD of 0.50% NaCMC treated soil imitated a similar trend of soil, inferring that no new chemical compounds formed with the reaction of soil and clay minerals. However, the anionic nature of NaCMC tends to attract the hydrated clay surface, resulting in intermolecular hydrogen bonds that enhance the strength [56]. Hence, the overall mechanism of strength improvement has been summarized as shown in Figure 9. The viscous gel bound the soil particles up to the optimum dosage and enhanced the soil strength. Microscopically, the NaCMC forms viscous gel threads to bridge the soil. Similar behaviour was observed with xanthan gum- and guar gum-treated soil by Kumar and Sujatha [22].

At higher dosages, the excess of NaCMC envelops the soil particles and prevents soil–soil interaction. This hinders natural cohesion, causing a strength reduction in the soil [46,47]. Microscopically, excess gel threads prevented contact between the particles (Figure 8). Although the viscous gel helped bind the soil and enhanced its strength, it could not compensate for the natural cohesive force exerted by the soil particles.

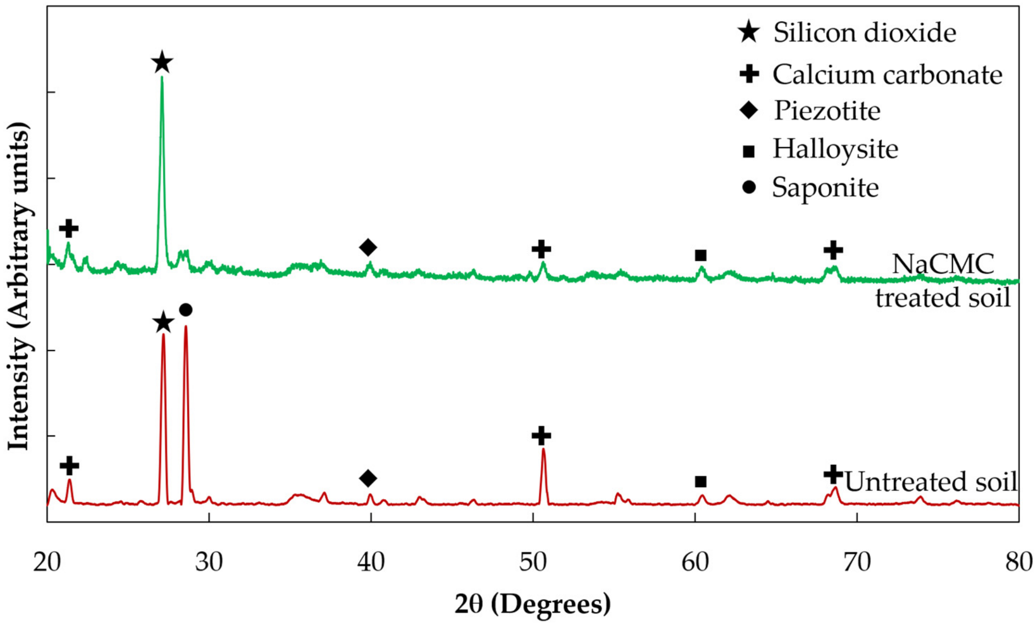


Figure 8. XRD diffractograms of untreated and NaCMC-treated soil.

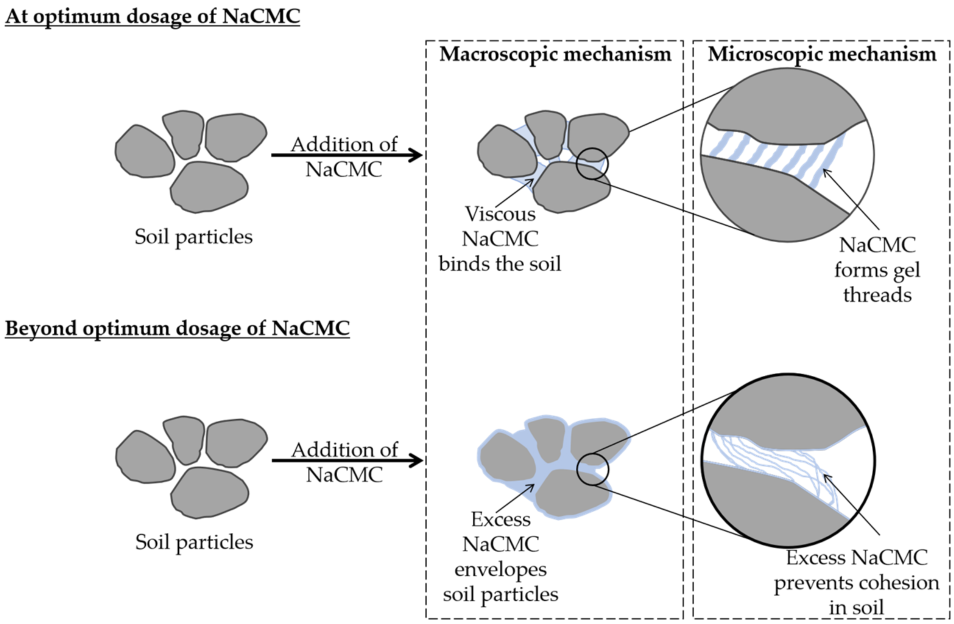


Figure 9. Mechanism of strength improvement.

4.3. HC

Hydraulic conductivity indicates the ease of water flow in a soil matrix and assesses the suitability of soil for liner material applications and use as a construction material in the core of earthen dams. The hydraulic conductivity of untreated soil is 8.78×10^{-8} cm/s. The HC of NaCMC-treated soil is shown in Figure 10a. The experimental results indicate that the addition of NaCMC reduced the HC with an increase in the dosage. Initially, at 0 days, the HC was reduced to 2.92×10^{-8} cm/s and 1.21×10^{-9} cm/s with 0.25% and 1.00% NaCMC, respectively.

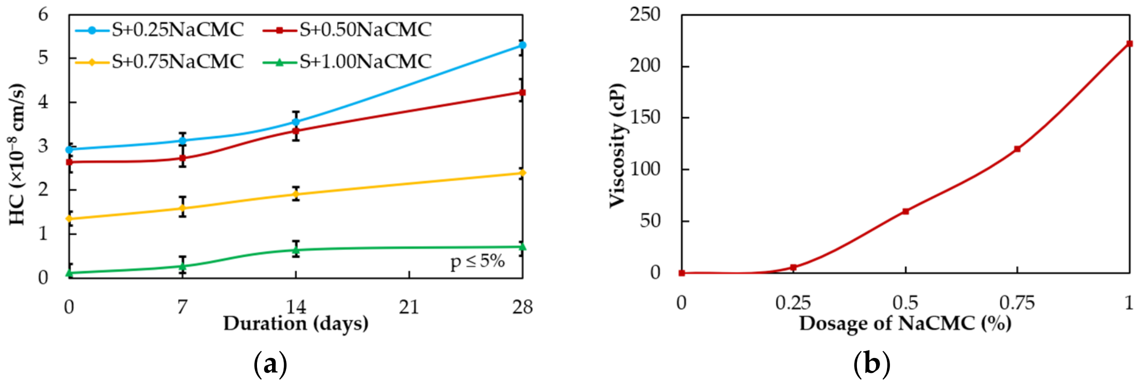


Figure 10. Variation in (**a**) HC; (**b**) viscosity with the dosage of NaCMC.

The decrease in HC at higher dosages can be attributed to the moisture-retaining capacity and the viscosity of NaCMC. Ning et al. [32] suggest that NaCMC forms a viscous gel and plugs the voids, preventing water infiltration [32]. The viscosity of NaCMC solution (Figure 10b) increased with dosage, confirming Ning et al.'s [32] theory. The excess NaCMC at higher dosages plugged the voids withholding the free flow of water. Additionally, the hydrophilic nature of NaCMC increased with dosage, making the soil adsorb more water. With ageing, the moisture-retaining capacity of the soil reached its peak value, and the complete saturation of the soil media created an aggregation effect resulting in a slight increase in the HC. Kumar and Sujatha [22] observed a similar increase in HC on xanthan gum, guar gum and β-glucan amended clayey sand after 120 days. After 28 days, the HC increased to 5.30×10^{-8} cm/s and 7.21×10^{-9} cm/s with 0.25% and 1.00%. This minimum increase in HC still remains lower than that of the untreated soil, indicating that NaCMC has a good potential to reduce the HC of the soil.

4.4. Compressibility Characteristics

Compressibility parameters symbolize the effect of structural settlement built over the soil in the long run. The compressibility behaviour of the soil is described in terms of three parameters, namely, coefficient of consolidation (c_v), which indicates the rate of consolidation; the compression index (c_c), which implies the magnitude of compression in the soil while loading; and swell index (c_s), which denotes the expansion potential of the soil during unloading. The results of the one-dimensional consolidation test are given in Table 4.

Table 4. Consolidation characteristics of the NaCMC treated soil.

Dosage	S	S + 0.25% NaCMC	S + 0.50% NaCMC	S + 0.75% NaCMC
c_v (m^2/year)	0.12	0.08	0.06	0.06
c_c (no units)	0.97	0.88	0.87	0.84
c_s (no units)	0.05	0.08	0.08	0.08

The c_v for the study is found by Taylor's square root of time method. A small addition of 0.25% NaCMC to the soil reduced the c_v from 0.12 m^2/year to 0.08 m^2/year. The c_v further reduced to 0.06 m^2/year at 0.50% NaCMC and maintained a constant value at higher dosages. The increased viscosity of NaCMC and the moisture-holding capacity of NaCMC-treated soil prevented the dissipation of pore water from the soil causing a reduction in the c_v. This behaviour of treated soil also affected the c_c, which denotes the void ratio variation with applied pressure. A negligible reduction in the c_c was observed as the compressibility of the soil is reduced with the addition of CMC. A slight increase in the c_s was observed due to the repulsion caused by the NaCMC gel around the soil particles.

Similar behaviour of reduced c_v, c_c and increased c_s was observed by Abd et al. [33] on low plastic clay treated by CMC.

4.5. Reaction in Extreme Environments

The untreated soil altered the pH of the acidic solution from 3.38 to 8.23 and showed negligible variation in the pH of the alkaline solution which changed from 12 to 11.83. Carvalho and Raij [57] suggested that calcium carbonate can neutralize the acidic nature of soil. XRD analysis in Figure 8 indicates that the study soil has calcium carbonate in it. This explains the increase in pH of the acidic solution after passing through the untreated soil, which has calcium carbonate in it. The pH of acidic and alkaline solutions changed to 7.86 and 7.21 with 0.5% NaCMC treatment in the soil. Adding NaCMC binds the soil particles; hence, the reactive sites are fewer when compared to untreated soil. This explains the reduced neutralization effect in NaCMC-treated soil than in untreated soil. Lee et al. suggested that biopolymers have the tendency to reduce the pH marginally [58]. In addition to that, the acidic nature of NaCMC (Table 1) reacted with alkaline solution to neutralize the pH. More importantly, the moisture-holding nature and the salt-inhibiting behaviour [59] of NaCMC helped reduce the pH of the alkaline solution. This proves that NaCMC has the potential to neutralize alkalinity in the soil effectively.

4.6. Practical Applications

The experimental results assure that NaCMC can effectively improve the UCS and reduce the HC of the treated soil. This shows that the additive has beneficial applications in strengthening the foundation-bearing strata, improving the capacity of pavement subgrades, and as water-retaining layers in pavements and landfill liners. The present study advocated using dry mixing of soil and additive, which can be done similarly to cement and lime treatment of soils. Paul and Hussain [60] attempted to stabilize 20% organic soil with a minimum of 5% cement. The commercial grade of NaCMC is available for a cost of INR 150/kg and cement are available for the lowest price of INR 8/kg [61]. Adopting a similar mixing method, the cost of 0.5% NaCMC treatment is 46.6% higher than 5% cement stabilization for 1 m^3 of soil. However, field applications and market demands will increase the use of biopolymers and substantially reduce their production cost.

5. Conclusions

The study attempted to explore the potential of environmentally friendly NaCMC as a viable material for soil and subgrade stabilization. In 28 days, 0.50% NaCMC enhanced the strength of the treated soil by 76.74%, establishing it as the optimal dosage for strength improvement. The treated soil exhibited a gradual post-failure response with increased resistance to failure. Although no new chemical compounds were formed, the viscous gel threads of NaCMC contributed to the strength gain. Moreover, the CBR of the soil improved by 33.19% with the optimum dosage of additive. The viscous gel plugged the voids and reduced the HC of 1% NaCMC-treated soil by 91.80% in 28 days. 0.50% NaCMC reduced the consolidation rate by 50% and increased the swell potential by 60% during unloading. The optimum additive dosage inhibited the penetration of dissolved salts through the soil and neutralized the alkalinity.

The study shows that NaCMC was a superior additive in terms of strength and hydraulic conductivity but could not prevent soil swelling. Although the study analyzed NaCMC's potential as a soil stabilizer, further research with a wide variety of soil and test conditions is recommended before field applications. Even though the treated soil did not display any signs of degradation during the study period, further research on the long-term geotechnical performance at extreme environmental conditions is required to establish NaCMC as a competitive soil stabilizer.

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