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A study on the efficacy of low viscous nanosized biopolymer on the mechanical and hydraulic properties of organic silt

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Abstract. Biopolymer stabilization is a sustainable alternative to traditional techniques that cause a lesser negative impact on the environment during production and application. The study aims to minimize the biopolymer dosages by sizing the bio-additives to the nanoscale. This study combines the advantages of bio and nanomaterials in geotechnical engineering applications and attempts to investigate the behaviour of a low viscous biopolymer, nano sodium carboxymethyl cellulose (nCMC), to treat organic soil. Soil is treated with 0.25%, 0.50%, 0.75% and 1.00% of nano-bio additive, and its effect on the plastic behaviour, compaction characteristics, strength, hydraulic conductivity (HC) and compressible nature are investigated. The strength increased by 1.68 times after 90 days of curing at a dosage of 0.5% nCMC through the formation of gel threads connecting the soil particles that stiffened the matrix. The viscosity of 1% nCMC increased exponentially, deterring fluid flow through the voids and reduced the HC by 0.85 times after curing for 90 days. Also, beyond the optimum dosage of 0.50%, the nCMC forms a film around the soil particles that inhibits the inter-particle cohesion causing a reduction in strength. Experimental results show that nCMC can effectively substitute conventional additives to stabilize the soil.

Keywords: cellulose; CMC; nano; UCS; viscosity

1. Introduction

Chemical stabilization of soil is a popular and common technique that is more effective than mechanical stabilization methods like stone columns or dewatering methods and reinforcement, etc., for projects with budget constraints (Kannan and Sujatha 2021). Conventional additives to the soil are usually cement, lime and fly ash. Cement and lime have been used for various soil types under different environmental conditions with proven results and economic viability. However, the recent concerns about environmental pollution and greenhouse emissions question their choice as cement and lime production industries are one of the major contributors to global carbon dioxide emissions (Garside 2021a, b). Additionally, cement stabilization of soil is not suitable when the organic content is greater than 2%, according to the American Concrete Institute guidelines (Firoozi *et al.* 2017).

In the past two decades, many environmentally friendly alternatives have been considered for research and field applications. Chief among them are fibre reinforcement (Nezhad *et al.* 2021), microbially induced calcite precipitation (MICP) (Choi *et al.* 2020), biopolymer stabilization, treatment with natural substitutes like wollastonite (Nikhil *et al.* 2020), marble dust (Yorulmaz *et al.* 2021) and industrial wastes like flyash (Nath *et al.* 2017) & rice husk ash (Basha *et al.* 2005). Fibres showed a better improvement in strength by adhering to the soil mass and bridging the void spaces in the soil matrix. Additionally, fibre treatment also offered a gradual plastic post-failure response (Tang *et al.* 2007). However, the capacity of the fibre is limited as the interactions are purely physical (Estabragh *et al.* 2014). MICP is yet another emerging technique for stabilizing soil in which the calcite precipitated by natural processes through bacterial excretions is used to improve the soil properties. Despite the advantages of higher strength gain and minimal soil pollution, the method suffers from limitations like issues with practical applicability as the microbial growth depends on the bacterial type, ambient environment and soil conditions (Soundara *et al.* 2020). Soundara *et al.* (2020) reported that the method is influenced by soil gradation and is suitable for soil with particle sizes ranging from 50 to 500 microns. Further mishandling of materials like flyash may pollute the soil and affect the intrinsic behaviour of the soil (Blaha *et al.* 2008). Also, particulate flyash materials can harm humans while handling (Blaha *et al.* 2008). On the other hand, biopolymers have environmentally friendly production methods and offer phenomenal improvement in the engineering characteristics of the soil. A range of well-established biopolymers like xanthan gum (Latifi *et al.* 2016, Bağrıaçık and Mahmutluoğlu 2021), guar gum (Sujatha and Saisree 2019), alginate (Arab *et al.* 2019, Fatehi *et al.* 2019), Persian gum (Ghasemzadeh and Modiri 2020), gellan gum (Chang and Cho 2019), chitosan (Hataf *et al.* 2018) etc. has shown appreciable improvement in the properties of coarse-grained and fine-grained soils.

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Most biopolymers form a viscous gel when added to water, and the viscosity increases with dosage. The viscosity of the biopolymer depends on various factors like concentration, molecular weight, nature of the biopolymer, shear rate and temperature. Typical examples include extremely low viscous biopolymers like Arabic gum which has a viscosity of 1.26 cP (Gómez-Díaz *et al.* 2008), and extremely high viscous biopolymers like xanthan gum which possesses a viscosity of 3639 cP in 2% aqueous solution (Kumar and Sujatha 2021). However, highly viscous biopolymers pose practical difficulties while mixing as it tends to aggregate (Patel *et al.* 2020), hindering uniform dispersion in the water to form the gum. Literature shows that low viscous (Ghasemzadeh and Modiri 2020) and non-viscous (Kumar and Sujatha 2021) biopolymers can also significantly improve the strength, which would be helpful in easy mixing during field application than using high viscous biopolymers.

Cellulose is the world's most abundant biopolymer in the cell walls, woody parts of plants, and a few bacteria (Knabner and Amelung 2013). Sodium carboxymethyl cellulose (CMC) is an anionic water-soluble polysaccharide (Ergun *et al.* 2015) and has wider applications as flocculating, thickening, water-retaining and film-forming agent (Chen 2015). Taylor and Baldridge (1954) analyzed the effect of CMC on aggregation, plasticity index and permeability on different types of loam and clay. The authors observed an increase in the plasticity index and permeability at higher dosages of CMC. Also, an enhanced aggregation effect was observed at higher CMC dosages. Ma and Ma (2019) investigated the mechanical properties of loess stabilized with CMC and reported that the strength of the treated soil improved from 2.07 MPa to 4.11 MPa and soil treatment with a dosage of 1.00% would be sufficient for the construction of low-rise buildings. Ning *et al.* (2019) compared the water infiltration capacity of CMC and polyacrylamide-treated sandy loams. Results showed that CMC is more effective in reducing soil water infiltration than polyacrylamide, with an increase in mean infiltration time by 84.75% for CMC-treated soil. Owji *et al.* (2021) reported that CMC has better durability against wind erosion than guar gum through their experimental investigations. Abd *et al.* (2022) investigated the geotechnical parameters of CMC improved low plastic clay and reported that CMC increased the plasticity index and decreased the consolidation parameters of the soil. These results show CMC would be a promising additive for soil stabilization.

Another contemporary development of the decade is nanotechnology and the research on its wider applications. Nanomaterials have found a prominent place in civil engineering in recent years. Several researchers in the past have investigated its applications in building engineering, water treatment and ground improvement. These nanomaterials being smaller in size, has a high specific surface area which offers better interaction with the surrounding material (Yokoyama *et al.* 2018, Gamallo *et al.* 2020), making them more suitable for applications like soil stabilization (Changizi and Haddad 2017, Kannan and Sujatha 2022) and strengthening of concrete (Norhasri *et al.* 2017). Their ability to interact with the surrounding materials is higher, and their tendency for greater solubility (Ravichandran 2009) helps in the coagulation of impurities in water treatment (Shabani *et al.* 2021). The installation of nano-sensors for building monitoring widened the potential of nanomaterials in the field (Karthick *et al.* 2019). Earlier literary reports claimed that materials like nano-silica (Changizi and Haddad 2016), nano-calcium carbonate (Mohammadi *et al.* 2021, Kannan *et al.* 2022), clay nanoparticles (Abbasi *et al.* 2018) and nano carbons (Taha *et al.* 2018) offer better strength of the treated soil. Beneficially, the quantity of the additives required in nano size would be much lesser than the same additive in conventional size as the reactivity of the material increases with the reduction of size (Majeed and Taha 2013).

In recent times, more research on nano carboxymethyl cellulose (nCMC) is emerging in various fields of science to utilize their smaller particle size. Saboori *et al.* (2018) found that nCMC has potential benefits in use as a drilling fluid rather than conventional synthetic fluid, owing to its superior rheological properties than bulk CMC. Tabari (2018) showed that nCMC has better mechanical, thermal and sorption capabilities and claimed better applications in food packing and pharmaceutical industries, even in smaller dosages. Qiu *et al.* (2021) used nCMC to repair the defects in carbon fibre-reinforced polymers. Results showed that nCMC enhanced the mechanical properties up to an optimum dosage of 0.075 g and formed polar groups over the defective surfaces. However, excess nCMC beyond optimum dosage disrupts the distribution of carbon fibres in carbon fibre-reinforced polymers.

This study aims to combine the advantages of biomaterials and nanomaterials in soil stabilization by introducing bio-nano materials for soil stabilization. With the proven effects of CMC in ground improvement and nCMC in biomedical fields, the study utilizes low viscous nCMC to investigate the geotechnical properties of low plastic silt with organic content. The study investigates the effect of viscosity on the Atterberg's limits, compaction nature, strength parameters, hydraulic conductivity (HC) and consolidation characteristics of the soil treated with 0.25%, 0.50%, 0.75% and 1.00% nCMC. The strength and hydraulic conductivity of the samples were examined for various curing periods (0 days, 7 days, 14 days, 28 days, 56 days and 90 days). Further, the mechanism behind the behavioural changes in the treated soil are investigated by the morphological changes using SEM and FESEM imaging, chemical variations using XRD, & functional group variations through FT-IR and document the practical advantage of using a low viscous biopolymer for treating organic soil.

2. Materials

The soil used for the study was collected from the Ariyalur district of Tamil Nadu state in India. Soil was black in colour and was classified based on the liquid, plastic limit tests (ASTM D4318 2017), organic content (ASTM D2974 2020) and grain size analysis (ASTM

Table 1 Geotechnical properties of the soil

Property	Value
Liquid limit (%)	48.8
Plasticity index (%)	22.9
Specific gravity	2.3
Differential free swell index (%)	35
Organic content (%)	13.6
Maximum dry unit weight (MDUW) (kN/m^3)	16.8
Optimum moisture content (OMC) (%)	17.5
Unconfined compression strength (UCS) (kPa)	172.4
Hydraulic conductivity (x 10^{-8} cm/s)	8.8
Coefficient of consolidation (m^2/year)	0.12

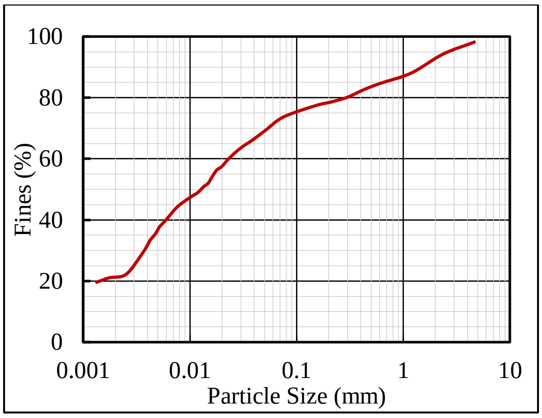


Fig. 1 Grain size distribution plot

D6913 2017, ASTM D7928 2021). The results of the preliminary geotechnical investigations, including the specific gravity (ASTM D854 2014), differential free swell index (IS 2720-40 1977), compaction characteristics (ASTM D698 2012) etc., are listed in Table 1.

The soil is predominantly silt (54%), and its grain size distribution plot is shown in Fig. 1. The soil has been classified as low plastic silt with organic content (OL) as per the Unified Soil Classification System (ASTM D2487 2017). The differential free swell index of the soil was 35%, indicating that the soil has a moderate tendency to swell.

nCMC is a nanosized, anionic and ether derivative of natural cellulose. nCMC readily dissolves in water and forms hydrogel. Cellulose is hydrophilic but insoluble in water due to the inter and intramolecular hydrogen bonding formed with adjacent chains (Eo *et al.* 2016). However, CMC, the ether derivative of natural cellulose, induces water solubility in the material. This nCMC is hydrophilic and tends to absorb more water than conventional cellulose. The nCMC used in the study was purchased from Nano Research Lab, Jharkhand, India. The material was yellowish-white in colour. The material properties of the nCMC used for the study are listed in Table 2.

The viscosity of 0.25% nCMC solution is 6.9 cP, and it increased exponentially to 59.1 cP for 1.00% solution at a shear rate of 132s^{-1} as shown in Fig. 2. The viscosity of 1% nCMC solution is much lesser than 1% xanthan gum and guar gum solutions (Kumar and Sujatha 2021). Hence nCMC can be regarded as a low viscous biopolymer.

Table 2 Material properties of nCMC

Property	Value
Molecular formula	$C_8H_{16}NaO_8$
Purity (%)	99.5
Average particle size (nm)	<100
Specific surface area (m^2/g)	40 – 60
True density (g/cc)	1.6
Molecular weight (g/mol)	263.2
Melting point (°C)	274
pH (10g/l at 25°C)	6.1
Viscosity (cP) (10g/l at 25°C)	59.1

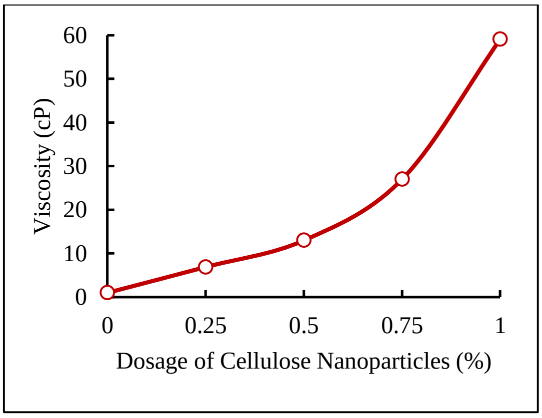


Fig. 2 Viscosity of nCMC solution

3. Methods

3.1 Soil preparation

The soil was excavated from a depth of 1.5 m to avoid the agricultural wastes in the field. Pebbles, dry roots and other undesirable materials were removed from the soil by hand-picking. The soil was then air-dried and sieved to the required gradation as per the experimental requirements.

3.2 Additive mixing method

The dosage on nCMC was fixed as 0.25%, 0.50%, 0.75% and 1% by dry weight of soil after trials with a wide range of nCMC dosages. Dry mixing was adopted for this study (i.e.,) additive was mixed thoroughly with the soil before adding water. Chang *et al.* (2015) suggested that dry mixing of biopolymer is more effective when soil strengthening is the primary concern. The viscosity of biopolymer solution increases with dosage of the additive, causing a reduction in solubility during wet mixing. This makes dry mixing preferrable (Chang *et al.* 2015). Further, Ergun *et al.* (2015) stated that CMC tends to form lumps when in contact with water. Dry mixing avoids the formation of aggregates/lumps and enables a uniform spreading of the additive.

3.3 Liquid limit and plastic limit tests

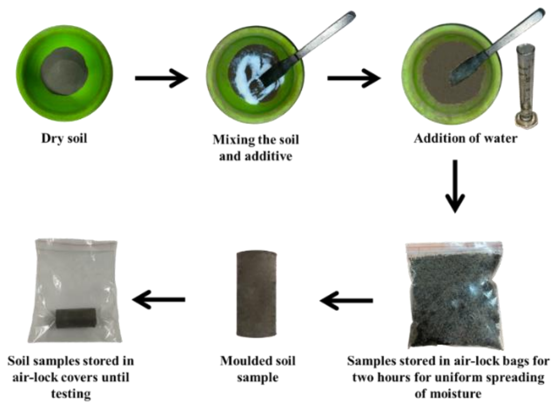


Fig. 3 Cylindrical samples preparation and curing procedure

The Atterberg's limit of the additive-treated soil was carried out based on the ASTM standards (ASTM D4318 2017).

3.4 Compaction test

The compaction characteristics of the treated soil were studied based on the guidelines outlined in ASTM D698 (2012). The soil was initially mixed with the desired dosage of additive, followed by adding 10% of water and was allowed to rest in air-lock covers for 2 hours before the compaction tests to ensure uniform hydration of the soil samples and promote chemical interaction, if any.

3.5 Unconfined compression test

Unconfined compression (UCC) test adhering to ASTM D2166 (2006) was carried out to understand the strength behaviour of the treated soil. The UCC test was conducted at a strain rate of 1.25 mm/min on cylindrical samples with 38 mm diameter and 76 mm height, prepared at their OMC. Fig. 3 explains the dry mixing of additive with the soil, followed by addition of water, followed by sample moulding. The moulded samples were cured in air-lock covers at room temperature until the test period (0 days to 90 days). The initial (0 days) testing was done after two hours of curing to allow for hydration.

3.6 Hydraulic conductivity test

The HC of the treated soil was observed for 90 days to understand the long-term effects following ASTM D5856 (2015). The samples were in continuous saturation for the entire test period.

3.7 Consolidation test

The compressible nature of the untreated soil and soil treated with 0.25%, 0.50% and 0.75% nCMC were investigated based on one-dimensional consolidation test following ASTM D2435 (2020). The test samples were 60 mm in diameter and 20 mm in height. The samples were loaded at pressure ranging from 10 kPa to 320 kPa and was unloaded gradually.

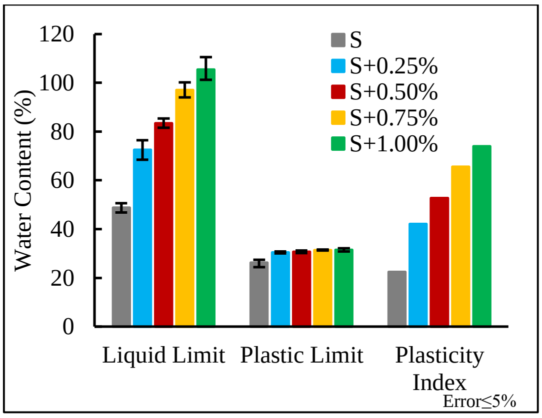


Fig. 4 Variation in the Atterberg's limits of nCMC treated soil with dosage

3.8 Material characterization tests

The viscosity of nCMC dissolved in water was tested for various dosages using Brookfield LVDV II + Pro viscometer to understand the strength improvement mechanism at different viscosities. Microstructural analysis was carried out using TESCAN Vega 3 scanning electron microscope (SEM) instrument and Zeiss Gemini field emission scanning electron microscope (FESEM) instrument. The functional group variations in the treated samples were studied using Bruker alpha Fourier transform infrared spectroscopy (FT-IR) instrument for a wavenumber ranging between 4000 cm^{-1} to 500 cm^{-1}. X-Ray Diffraction analysis using Bruker XRD instrument was carried out for a 2θ range of 20° to 80° to check the potential chemical changes involved in the treated samples.

4. Results and discussions

4.1 Atterberg's limits

The liquid limit (LL) is the threshold water content at which soil possesses a minimum shear strength. The soil has a liquid limit of 48.8%, falling in the border line of low and high compressibility. The addition of 0.25% to 1.00% nCMC at 0.25% increment significantly increased the LL to 72.48%, 83.44%, 97.05% and 105.36%, respectively, as shown in Fig. 4. This increase in viscosity with dosage increases the pore fluid concentration of the nCMC in the soil-nCMC-water matrix (Nugent *et al.* 2010). Consequently, the hydrophilic nature of the nCMC (Qin 2016) increased the tendency of the soil to absorb water, causing an increase in the LL of the treated soil, indicating that the treated soil would have shear strength even at higher water content.

The plastic limit is the limiting water content below which soil develops rupture under deformation. The soil has a plastic limit of 26.30% and increases to 30.43% upon adding 0.25% nCMC. With a further increase in dosages, the plastic limit remained almost constant at a water content of approximately 31%, which is a marginal increase. Results show that a moisture content of around 31% is

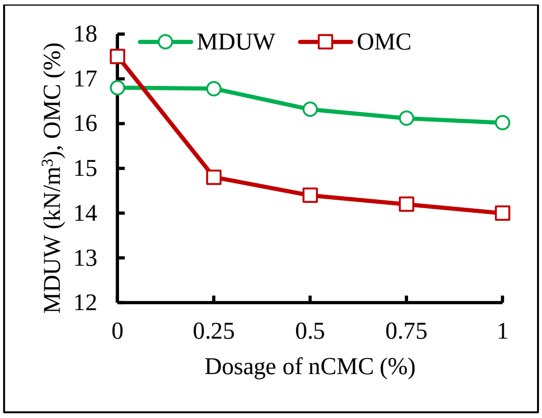


Fig. 5 MDUW and OMC of nCMC-treated soil

sufficient to prevent rupture formation in the additive-treated soil despite the increase in the dosage. Upon comparing the results of the liquid limit and plastic limit in Fig. 4, the hydrophilic nature of the treated soil is noticeable when the water content is beyond the plastic limit.

The plasticity index is the range of water content between liquid and plastic limits, at which soil deforms plastically without deformation and without losing shear strength. The soil has a plasticity index of 22.5%. The steep increase in the LL and the marginal change in the plastic limit resulted in an increased plasticity index of the soil. The treated soil retained the excess water during the tests and behaved like deformable material, indicating that the soil remains plastic and cohesive for a broader range of water content before it starts flowing like a liquid. Similar behaviour of increased liquid limit and plasticity index was observed by Abd *et al.* (2022) on soft low plastic clay treated with CMC.

4.2 Compaction characteristics

OMC is the water content at which the soil attains the MDUW under compaction effort. Compacting the soil at their MDUW and OMC tends to reduce the soil's susceptibility to settlement. The untreated soil has an MDUW and OMC of 16.8 kN/m^3 and 17.5%, respectively. The addition of nCMC shifted the compaction curves to the left in the downward direction, indicating that both MDUW and OMC of the treated soil decreased with an increase in the dosage of nCMC. OMC decreased substantially to 14% at 1.00% nCMC treated soil, and MDUW marginally lowered to 16.02 kN/m^3 at 1.00% nCMC treatment, as shown in Fig. 5.

The initial 10% water created an aggregation effect, where the nCMC forms a viscous gel with water in the soil matrix tending to aggregate the soil particles surrounding it. A similar aggregation effect was earlier reported by Taylor and Baldridge (1954) on NaCMC-treated soils. With compaction effort, the soil is compressed in an aggregated state. Although the additive is hydrophilic, the higher viscosity of the additive at larger dosage created a strong adhesion between the particles in the aggregated soil mass, preventing further imbibing of water in the soil-additive matrix. This behaviour caused the soil particles to pack at lower MDUW at a lesser OMC, which is typical behaviour of the organic soils. Kannan and Sujatha (2022) observed similar behaviour on the organic soil treated with nano-silica, where the soil experienced an aggregated effect due to the hydration reaction formed with nanoparticle addition.

Table 3 Failure strain of nCMC treated soil with ageing

Curing Period	Dosage of nCMC			
	0.25%	0.50%	0.75%	1.00%
0 days	6.25%	6.25%	6.25%	5.92%
7 days	5.92%	5.92%	5.92%	5.92%
14 days	5.59%	5.59%	5.26%	5.26%
28 days	5.26%	5.26%	5.26%	5.26%
56 days	4.93%	4.93%	4.93%	5.26%
90 days	4.93%	4.93%	4.61%	4.61%

4.3 Strength characteristics

4.3.1 Stress-strain response

The stress-strain response of nCMC-treated soils for various curing periods is shown in Fig. 6. The stress-strain curves show a gradual post-failure response without a definite peak or sudden reduction in the stress past peak load. Adding nCMC induced plastic behaviour in the treated soil and the failed samples experienced bulging accompanied by vertical cracks. This plastic behaviour was noticed at all the curing periods investigated with all the dosages.

4.3.2 Failure strain

The failure strain denotes the maximum deformation experienced by the soil at impending failure. The soil failed at a strain of 4.61%. The addition of nCMC increased the failure strain owing to the plastic nature induced by the additives on the soil. The failure strain of the treated soil with ageing for various dosages of nCMC is presented in Table 3. Table 3 shows that the failure strain of nCMC-treated soil samples reduced with both ageing and an increase in the dosage; however, at all times was greater than the untreated soil. The hydrophilic property of nCMC gave the soil a plastic nature, making the samples fail at a higher strain. At higher dosages, the increased viscous nature of the nCMC tends to resist the deformation causing the samples to fail at relatively lesser strain. Similarly, at higher curing periods, the gel threads formed by the nCMC addition resist the deformation imparting brittle nature to the treated soil matrix, causing it to fail at a lower strain.

4.3.3 Failure modulus

The failure modulus is an indirect measure of the resistance offered by the soil to the applied load. Untreated soil has a failure modulus of 3743.54 kPa. The failure modulus of the nCMC-treated soil with varying dosage and curing period is shown in Fig. 7. Results from Fig. 7 indicate that samples treated with 0.5% nCMC have a maximum failure modulus of 4232.32 kPa, 5800.15 kPa,

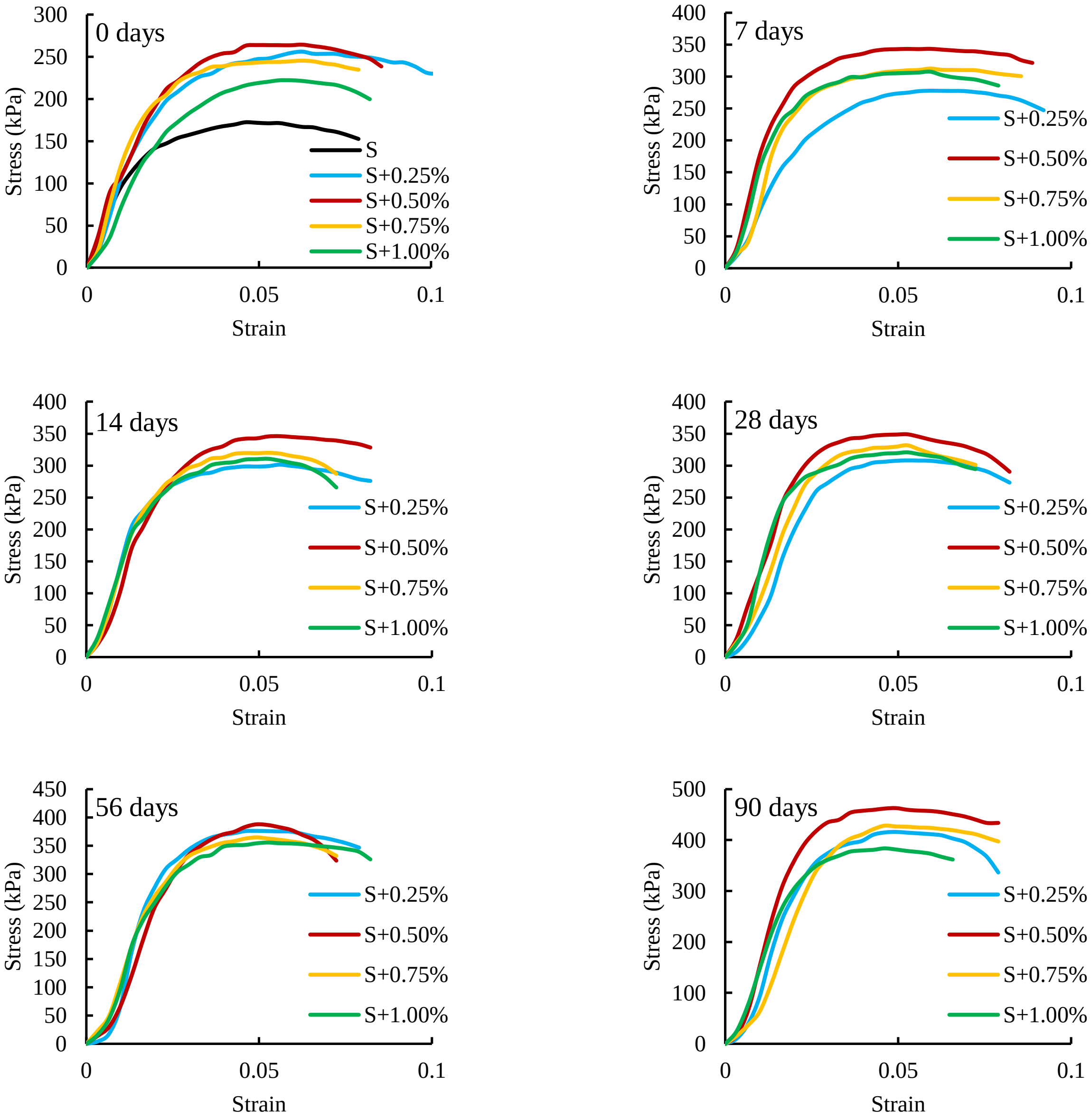


Fig. 6 Stress-strain behaviour of nCMC treated soil with ageing

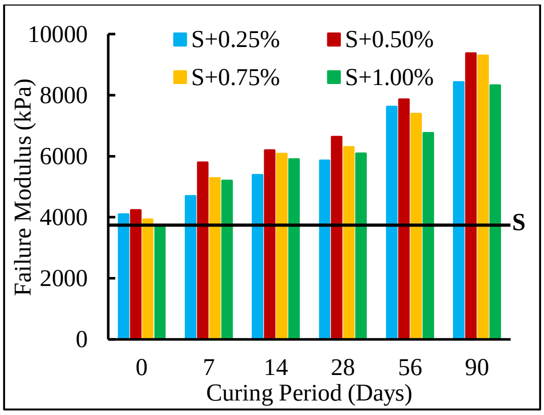


Fig. 7 Failure modulus of nCMC treated soil with ageing

6192.48 kPa, 6634.23 kPa, 7865.49 kPa and 9377.59 kPa at 0 to 90 days, respectively.

The greater failure modulus with ageing indicates that the soil developed resistance against loading and deformation with additive treatment. This increase in failure modulus indicates that with ageing, the 0.5% nCMC treated soil would be stiffer and more suitable if the soil has to bear more load from the structure while maintaining the settlement under control.

4.3.4 Unconfined compression strength

The strength of the treated soil plays a crucial role in its selection as a suitable material for ground improvement applications. The organic soil has a UCS of 172.4 kPa at its OMC. Adding nCMC improved the UCS of the treated soil at all the dosages and curing periods ranging between 0 and 90 days up to a dosage of 0.5% additive and reduced with further addition of nCMC. Fig. 8 shows the strength of the treated soil at various curing periods. Soil treated with 0.5%

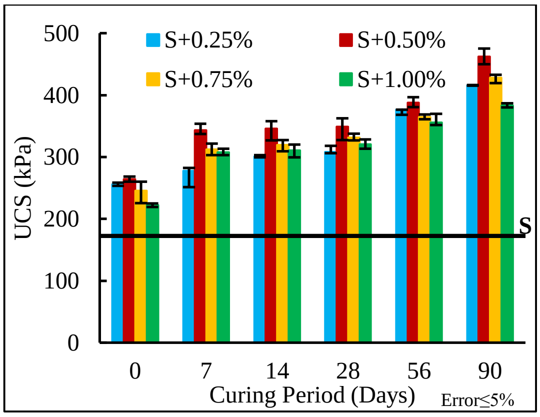


Fig. 8 UCS of nCMC treated soil with ageing

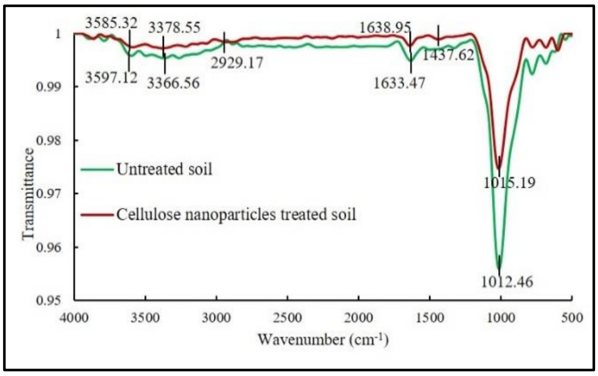


Fig. 9 FTIR Spectrum of nCMC treated soil

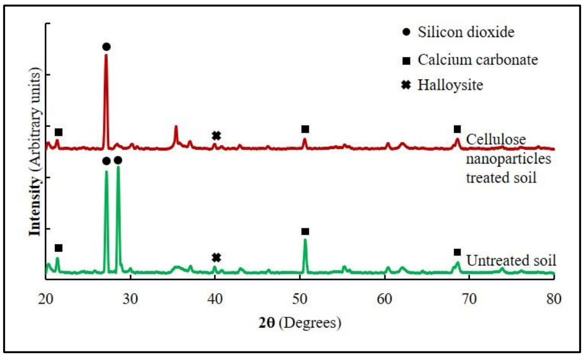
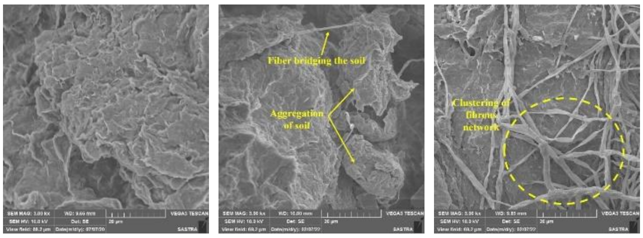


Fig. 10 XRD Spectrum of nCMC treated soil



(a) S (b) S+0.50% (c) S+1.00%

Fig. 11 SEM micrographs of nCMC-treated soil

nCMC showed strength improvement by 0.53, 0.99, 1.01, 1.02, 1.25, and 1.68 times after 0 days, 7 days, 14 days, 28 days, 56 days and 90 days of curing, respectively.

The mechanism of strength improvement varies with different types of biopolymers depending on various factors governing their physical and chemical properties. Viscous biopolymers like xanthan gum develop gel plug, gel threads and biofilm around the soil matrix (Kumar and Sujatha 2021), which plug the voids and improves the strength of the soil. Non-gellable biopolymers like β-glucan develop fibrous threads bridging the soil sample and enhancing the strength (Kumar and Sujatha 2021). Materials like guar gum and chitosan solution developed hydrogen bonding with the soil, enhancing its strength (Sujatha and Saisree 2019).

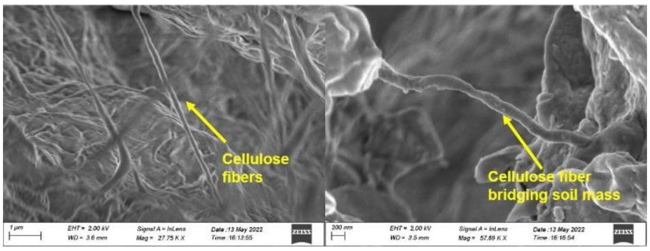
The FT-IR spectrum of the organic soil and nCMC-treated organic soil is shown in Fig. 9. The strong peaks around 1012.46 cm^{-1} and 1015.19 cm^{-1} in both treated and untreated soil indicate the presence of Si-OH alumino silicate lattice that points to the presence of clay minerals like kaolinite, smectite, illite etc. Tinti *et al.* (2015). The bands with wavenumbers around 3585.32 cm^{-1} and 3597.12 cm^{-1} denote the Si-O-H vibrations in the clay minerals present in the soil. Further, Tinti *et al.* (2015) mentioned that the regions around 3440 cm^{-1} to 3320 cm^{-1} indicate the O-H or N-H stretching and H- bonded OH groups, which was observed with the peaks at 3378.55 cm^{-1} and 3376.56 cm^{-1}. Berzins *et al.* (2019) and Tinti *et al.* (2015) stated the peak around 1638 cm^{-1} indicates the stretching vibrations in C=O and C=C groups. The formation of new minor peaks at 2929.17 cm^{-1} and 1437.62 cm^{-1} in the treated soil are in line with the FTIR spectrum of NaCMC, as observed by Lin *et al.* (2005).

XRD spectrum of the treated and untreated soil was investigated to identify the formation of new chemical compounds, if any, upon reaction with the soil. XRD spectrum in Fig. 10 shows that the soil has the presence of silicon dioxide, calcium carbonate and halloysite clay minerals. Similar mineral peaks in the XRD spectrum of untreated and additive-treated soil indicate that no new compounds are formed during the reactions, and the interactions are purely physical.

Ma and Ma (2019) also reported that NaCMC improved the soil strength only through the viscous gel formed by the dissolution of the additive in water, and no new chemical reactions were involved. The viscous nature of the nCMC created an adhesion, which binds the particles, causing an improvement in the strength up to the optimum dosage. Excess of additive beyond the optimum dosage envelops the soil particles forming a thin gel film which hinders the cohesive force, resulting in reduced UCS.

A morphological study using SEM was conducted on the untreated sample and on samples treated with 0.50% and 1.00% nCMC after 7 days of curing. SEM micrographs in Fig. 11(b) indicate that the treated soil developed fibrous threads which bridged the soil mass to enhance the strength. Also, nCMC promoted the aggregation of soil particles (Taylor and Baldridge 1954). But with an excess dosage of additive, the fibres formed a clustered network, as shown in Fig. 11(c) and reduced the interparticle adhesion leading to a reduction in strength.

In an attempt to understand the mechanism of strength gain and to optimize the nano-additive dosage for soil stabilization, high-resolution images at higher magnification were obtained using FESEM on nCMC-treated soil after 28



(a) Clustering (b) Fibre bridging

Fig. 12 FESEM micrographs of nCMC-treated soil

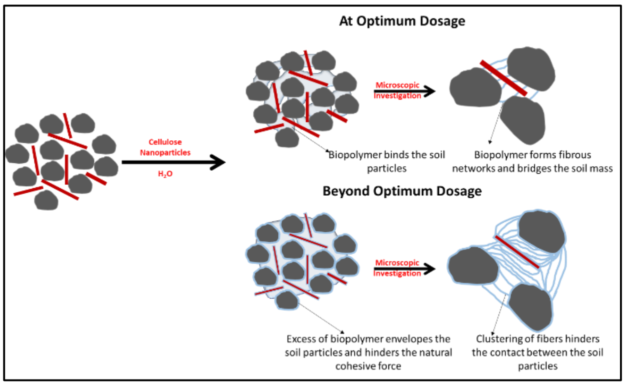


Fig. 13 Strength Improvement Mechanism

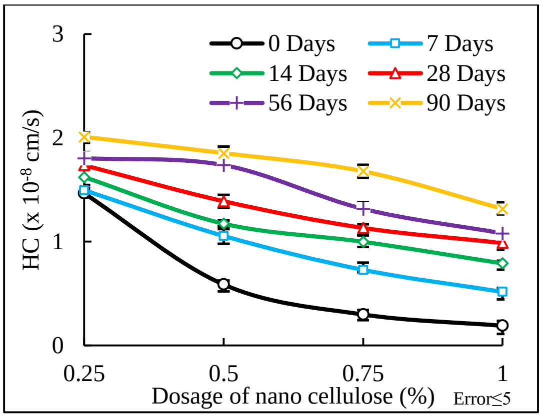


Fig. 14 HC of nCMC treated soil with ageing

days of curing with magnifications over 25kx and 50kx. The images are shown in Fig. 12.

The increase in magnification ensured that the fibrous threads formed with cellulose treatment connected the soil mass even in tiny pores. This indicates the effectiveness of nCMC in the strength enhancement of the treated soil. The mechanism behind the macroscopic and microscopic aspects of strength improvement is explained in Fig. 13.

4.4 Hydraulic conductivity

Hydraulic conductivity, or the coefficient of permeability indicates the ease of water flow through the soil. It is an important parameter while selecting soil for applications like core for earthen dams, landfill liners, slope/embankment formation and for use as a filter medium. The soil has an HC of 8.8×10^{-8} cm/s. The HC was slightly reduced with an increase in dosage of nCMC and showed an insignificant increase with ageing (Fig. 14). However, the HC of the treated soil remained lesser than the untreated soil. At complete saturation, the nCMC forms a viscous gel and plugs the voids of the soil sample, causing a reduction in HC. At higher dosages, the increased viscosity causes more resistance to water permeation. In addition, the water retention capacity of the nCMC increases with dosage (Ning *et al.* 2019). The continuous saturation of the sample during the HC test made the soil absorb and withhold more water forming the nCMC hydrogel, thereby reducing the HC (Ning *et al.* 2019). Beyond the point of complete water holding capacity of the treated soil, the soil started expelling the excess water causing a marginal increase with ageing.

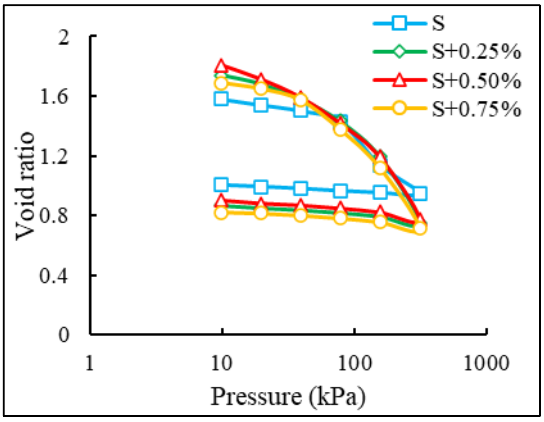


Fig. 15 e-log P plots of nCMC treated soil

Table 4 Consolidation parameters of nCMC treated soil

Consolidation Parameters	S	S+0.25%	S+0.50%	S+0.75%
c_v (m²/year)	0.12	0.10	0.08	0.06
c_c	0.97	0.73	0.70	0.68
c_s	0.046	0.053	0.054	0.055

4.5 Consolidation characteristics

Consolidation parameters determine the suitability of the soil as a load-bearing stratum for foundations indicating its susceptibility to settlement. One dimensional consolidation test quantifies the compressibility of the soil based on the coefficient of consolidation (c_v), compression index (c_c) and swell index of the soil (c_s). The study adopted the Taylor's square root of time method to determine the c_v. The e-lop plot used to determine c_c and c_s is shown in Fig. 15, and the test results are tabulated in Table 4.

Adding nCMC to the soil reduced the consolidation rate, as witnessed by decreased c_v. The increase in viscosity of the gel holds the soil mass together making the dissipation of pore water due to the applied pressure difficult (Abd *et al.* 2022). Further, the hydrophilic nature of the nCMC makes the dissipation of pore water difficult at higher additive dosages, causing a reduction in the coefficient of consolidation. This, in turn, affected the c_c of the soil, which denotes the change in void ratio per unit pressure. The reduction in c_c indicates that treated soil would undergo lesser settlement with an increase in pressure.

Results from Table 4 indicates that soil showed resistance to the applied pressure resulting in the reduced variations in the void ratio.

The treated soil showed negligible variation in the swell index. The slight increase in the swell index of the treated soil could be because of the repulsion caused by the nCMC coated over the soil while unloading. Abd *et al.* (2022) reported a similarly reduced c_c and a marginal increase in the c_s of the CMC-treated soft clay for a dosage ranging between 0.5% and 5.0%.

5. Conclusions

The study investigates the effect of low viscous nCMC on the engineering behaviour of a low plastic organic silt. The results showed an insignificant variation in the HC and a reduction in the coefficient of consolidation and compression index of the treated soil. In contrast, the UCS increased by 1.68 times after 90 days of curing. The addition of nCMC did not lead to the formation of any new chemical compounds in the soil but formed a microscopic fibrous network that bridged the soil mass. The initial addition of the additive in the nanoscale created an aggregation effect in the soil mass due to the adhesion created by the viscous nature of the nCMC. Further, the water retention capacity and pore plugging nature of the nCMC gel reduced the HC and hindered the dissipation of pore water pressure. The water-retaining hydrogel behaviour of the additive is more noticeable beyond the plastic limit of the soil; until then, the treated soil contributed to the engineering properties of the soil favourably. Also, the low viscous nature of the additive would be helpful in easy mixing and ground applications. However, the following are the concerns that need to be addressed before further promoting the material as a soil-stabilizing additive

- The study limits its scope to 90 days, where further investigation is required as cellulose is biodegradable.
- This study is yet another contribution towards a greater cause of sustainable ground improvement. Further investigation on the applicability of the additive for various types of soil is required in detail before promoting the material for practical applications.

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