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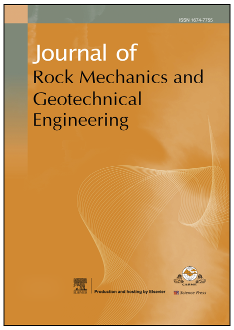

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Technical Note

Inhibition effect of swelling characteristics of expansive soil using cohesive non-swelling soil layer under unidirectional seepage

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A B S T R A C T

Cohesive non-swelling soil (CNS) cushion technology is widely used to solve swelling deformation problems in expansive soil areas. However, the swelling inhibition mechanism is still not fully understood. In this study, the inhibition effect on expansive soil using a CNS layer was studied by performing five types of laboratory model tests under unidirectional seepage. The results showed that CNS cushion technology produced a sound inhibition effect on the swelling characteristics of expansive soil. It was shown that the cations in the CNS layer moved downward and accumulated on the surface of solids and produced an electrical environment inside the expansive soil. In this process, the adsorbed hydrated cations participated in ion exchange with the expansive soil, leading to the modification effect on its swelling potential. Meanwhile, the adsorbed water membrane surrounding the expansive soil aggregates formed by the hydrated cations obstructed further adsorption of water molecules, which inhibited the swelling development of expansive soil. Therefore, the swelling inhibition mechanism can be attributed to three factors: (i) modification effect, (ii) electrical environment, and (iii) deadweight of the CNS layer. The combined contribution of modification effect and electrical environment can be considered as an electric charge effect, which mainly controls the swelling characteristics of expansive soil.

1. Introduction

Expansive soil is widely observed around the world, and it is extremely sensitive to variation of water content (Jones and Jefferson, 2012). Expansive soil swells upon absorption of water and shrinks upon evaporation (Chen, 1988; Nelson and Miller, 1997). Given this swell-shrink behavior, the safety and stability of constructions in expansive soil areas have attracted considerable attention (Petry and Little, 2002; Puppala et al., 2005; Rojas et al., 2006a, b). To mitigate or avoid the swell-shrink problem, various remedial techniques have been proposed, such as soil replacement (Chen, 1988), moisture control (Rojas et al., 2006a, b), application of adequate surcharge pressure (Chen, 1988), chemical alteration with different additives (Snethen, 1979; Cokca, 2001; Puppala et al., 2003; Murty and Praveen, 2008; Guda, 2016), and use of cohesive non-swelling soil (CNS) cushion technology (Katti, 1979; Katti et al., 1994).

Among these remedial techniques, the CNS cushion technology implemented in the subgrade, foundation, and cross-drainage structures has achieved a remarkable effect (Katti et al., 1994). In particular, according to the experiences of numerous studies on treatment of black cotton soil by means of a CNS layer, Katti et al. (1994) proposed tentative specifications for soil to be used as CNS material. However, its mechanism has not been clarified yet, so that there are some deficiencies in the recommended specifications. The inefficiency of CNS materials used at several engineering projects has been reported (Nagarkar et al., 1987; Rao et al., 1994), whereas some soil materials that do not meet these specifications have shown a potential to effectively inhibit expansive soil (Sahoo et al., 2008; Sahoo and Pradhan, 2010). Therefore, the mechanism of CNS cushion technology is a valuable research issue. A noteworthy experimental phenomenon is observed when the thickness of the CNS layer reaches approximately 1.2 m, that is, no heave is reported even under saturation condition, even though the swelling pressure (224 kPa) of the black cotton soil exceeds the deadweight of the CNS layer (Katti et al., 1994). This indicates that the swelling inhibition mechanism does not only depend on protection or deadweight of the CNS layer, but may be attributed to other factors controlling the swelling of expansive soil.

Accordingly, Katti et al. (1994) and Murty and Praveen (2008) speculated that the CNS layer would develop an electrical environment at and below the CNS–expansive soil interface, which contributed jointly with the overburden to the development of adsorbed water bonds between the clay mineral particles, and inhibited the swelling of the black cotton soil. However, due to the lack of test data, there is no scientific evidence to account for the mechanism of the adsorbed water bonds affecting the swelling characteristics of expansive soil. Thus, it is necessary to understand the interaction between the CNS layer and expansive soil, which is involved in the formation of an electrical environment in expansive soil.

Previous studies revealed that changes in types and concentrations of electrolyte in soil solution significantly affect the potential of soil surface and its electrochemical characteristics (Jenny and Reitemeier, 1935). For expansive soil carrying negative charges, its swell-shrink behavior is closely related to the type and concentration of cations in pore solution. Many researchers (e.g. Norrish and Quirk, 1954; Studds et al., 1998; Siddiqua et al., 2011; Thyagaraj and Rao, 2013; Ye et al., 2015; Zhu et al., 2015) have indicated that different electrolytes can lead to different swelling deformations of expansive clays. Meanwhile, it was demonstrated that the type of pore solutions could significantly influence the swelling characteristics of expansive soil (Di Maio, 1996; Herbert et al., 2008; Komine et al., 2009; Zhu et al., 2013; Chen et al., 2015; He et al., 2019; Xiang et al., 2019). Apparently, cations in the CNS layer will migrate with water molecules in the saturation process, thus affecting the concentration of electrolyte in the pore solution of expansive soil. Therefore, changes in the concentration of cations in soil solution will alter its electrochemical characteristics, which ultimately affect the macroscopic swelling characteristics of expansive soil.

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This paper tried to investigate the inhibition effect of CNS layer with different thicknesses on the expansive soil under saturated condition of unidirectional water injection. In the saturation process, variations in concentration of cations in the soil solution at different soil layers were obtained. Next, soil samples were taken at different soil layers from the test apparatus for determination of material parameters when model tests were completed. The cation concentration and swelling characteristics of these soil samples were measured and compared with their initial values. Then, it can be determined whether the cations in the CNS layer can migrate downward and aggregate to form an electrical environment. Finally, the swelling inhibition mechanism of expansive soil induced by the CNS layer technology was explored, providing a good basis for design and implementation of this technology for treatment of expansive soils.

2. Materials and methods

2.1 Materials and sample preparation

The expansive soil used in this study was sampled in Nanning, Guangxi Zhuang Autonomous Region, China. The non-swelling soil used was collected from Wuhan, Hubei Province, China. The basic physical and chemical properties of expansive and non-swelling soils are presented in Table 1.

Katti et al. (1994) proposed tentative specifications for soils as CNS materials, which are summarized in Table 2. Apparently, the non-swelling soil selected in this study does not meet the recommended requirements in Table 2. In fact, it is difficult to find natural CNS materials that fully conform to the specifications in Table 2 in practical engineering (Murty and Praveen, 2008; Sahoo et al., 2008). Therefore, for specific expansive soil, selection of a suitable CNS material and inhibition effect of the CNS on the expansive soil should be verified by experiments. In this study, the results showed that the selected non-swelling soil could significantly restrain the swelling characteristics of expansive soil. Therefore, the soil is regarded as a CNS material.

According to the method suggested in the Chinese code JTG E40-2007 (2007), naturally dried soil samples were crushed and passed through a standard 2-mm sieve, and then a target amount of water was added and thoroughly mixed to maintain the soil sample at the optimum moisture content (OMC).

2.2. Experimental scheme and setup

In this context, five types of laboratory model tests on the CNS layer were carried out, and the experimental schemes are listed in Table 3.

Table 3. Experimental schemes.

Test No.	Thickness of expansive soil (mm)	Thickness of CNS layer (mm)	Degree of compaction (%)
1	60	0	90
2	60	60	90
3	60	90	90
4	60	120	90
5	60	150	90

The schematic diagram of experimental setup adopted for model tests of the CNS layer is shown in Fig. 1.

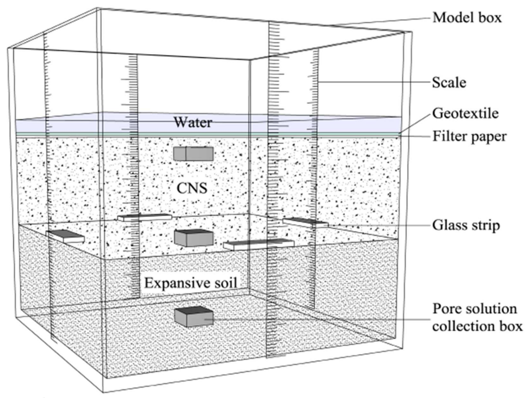

Fig. 1. Schematic diagram of experimental setup.

The dimensions of the model box are 30 cm × 30 cm × 30 cm and the outer surfaces are pasted with scales with an accuracy of 1mm. When de-ionized water was injected on the surface of the CNS layer, a filter paper was placed on it, and then one layer of geotextile was covered to eliminate the impact of water injection on the surface soil. Furthermore, the water lever was kept at 1 cm during model tests. Four glass strips with sizes of 10 cm × 2 cm × 0.5 cm were placed on four sides of the CNS–expansive soil interface. When the expansive soil swells, the position of the glass strips is changed. This variation can be measured by the scale on the outer surface of model box, which presents the swelling deformation of the expansive soil layer.

According to the method proposed by She et al. (2019), during saturation process, three pore solution collection boxes with sizes of 5 cm × 5 cm × 2 cm were used to extract the pore solution at three soil layers to analyze the regulation of cation migration from CNS layer, as shown in Fig. 1. It should be noted that there are many holes with diameter of 1 mm on the upper cover of the box, so that water can flow into the box. The entire body of the box was covered with one layer of filter paper to prevent soil particles from entering into the box.

Table 1. Basic physical and chemical properties of soils.

Soil	Grain size distribution (%)			Specific gravity	Unified soil classification	Concentration of main cations (mg/L)			
	Sand	Silt	Clay			Na^+	K^+	Mg^{2+}	Ca^{2+}
Expansive soil	3.9	31.7	64.4	2.7	High liquid limit clay	12.5	10	35	405.5
Non-swelling soil	1.4	64.2	34.4	2.73	Low liquid limit clay	7.5	20	75	217.5

Soil	Compaction properties (Standard Proctor)		Swell properties			Atterberg limits (%)	
	Optimum moisture content (OMC) (%)	Maximum dry density (MDD) (g/cm^3)	Free swelling ratio (%)	Swelling force (kPa)[a]	Swelling percentage (%)[a]	Liquid limit	Plastic limit
Expansive soil	16.2	1.8	65.5	182.72	19	63	24.94
Non-swelling soil	13.8	1.92	24.5	-	-	37.23	20.1

[a] Swelling force and swelling percentage were measured under the conditions of 90% compaction and OMC.

Table 2. Tentative specifications of soil as CNS material (Katti et al., 1994) based on experiences gained from studies under Malaprabha Right Bank Canal (MRBC) conditions.

Grain size analysis (%)				Consistency limits (%)			
Clay (<0.002 mm)	Silt (0.06–0.002 mm)	Sand (2–0.06 mm)	Gravel (>2 mm)	Liquid limit	Plastic limit	Plasticity index	Shrinkage limit
15–25	30–45	30–40	10	30–50	20–25	10–25	≥15

Swelling force of samples compacted to MDD under no-volume-change condition (kPa)		Clay minerals	Shear strength of samples compacted to MDD at OMC after saturation			Approximate thickness [a] of CNS layers for various swelling forces (m)		
At zero moisture content	At OMC		Half UCS (kPa)	Consolidated direct shear test at 0.0125 mm/min		100–150 kPa	200–300 kPa	350–500 kPa
				c (kPa)	ϕ (°)			
<10	<5	Preferably kaolinite and illite	15–35	10–30	8–15	0.75–0.85	0.9–1.00	1.05–1.15

[a] It is necessary to conduct large-scale tests to determine the optimum thickness of CNS layer with available CNS material.

2.4. Test procedures

2.4.1. Model elaboration

The soil samples were compacted in layers to reach the uniform density. The degree of compaction of each soil layer was controlled at 90% corresponding to the OMC. The inner wall of the model box was smeared with silicone grease to reduce friction between soil and inner wall. The collection boxes were placed at the top of the CNS layer, the CNS–expansive soil interface, and the bottom of the expansive soil, respectively, to collect the corresponding pore solution. Four glass strips were buried in each of the four sides of the CNS–expansive soil interface to observe the corresponding swelling deformation.

2.4.2. Cation concentration tests

Soil samples for cation concentration tests were crushed and passed through a standard 1-mm sieve, and dried at 105 °C. Then, a certain amount of de-ionized water was added to the dried soil samples. Subsequently, the supernatant was separated from the prepared soil suspension through centrifugation. Finally, the cation concentration of the supernatant was determined by the method suggested by Hach Company (2009).

The initial concentrations of the main cations in the pore solution of the CNS and expansive soil are presented in Table 1. From the second day after the model was injected with the de-ionized water, the pore solution in the collection boxes was extracted every 3–4 d for detection of cation concentration. Then, after completion of the model test, samples were taken from the top and bottom layers of the CNS and expansive soil, and then dried and crushed to measure their cation concentrations according to the same procedure as mentioned above.

2.4.3. Swelling tests

According to JTG E40-2007 (2007), soil samples for swelling tests were passed through a standard 0.5-mm sieve, dried at 105 °C until constant weight was reached, and then cooled down to room temperature. Free swelling ratio is defined as the ratio of the increasing volume of sample after fully swelling in presence of water to the original volume in air. Furthermore, swelling force, swelling percentage and loaded swelling ratio tests were performed on the same cylindrical samples with height of 20 mm and diameter of 61.8 mm. It should be noted that all cylindrical samples were compacted at the same moisture content (16.2%) and dry density (1.62 g/cm^3). The swelling force is defined as the pressure required to prevent the sample from swelling when it is immersed in water. The swelling percentage and loaded swelling ratio are determined as the ratio of the increased height of soil sample after water absorption to the original height. The sample used for swelling percentage test can merely expand vertically upon laterally constrained conditions. Conversely, the sample for loaded swelling ratio test can only expand under a certain pressure, which is considered equal to the saturated deadweight of the given CNS layer in each model test. Additionally, every swelling index of the above tests was determined by four parallel experiments.

3. Results and discussion

3.1. Swelling deformation of the expansive soil layer

During the model test, de-ionized water was injected on the top of the CNS layer to make soil fully saturated. The swelling deformation in each test used the average values of expansion at four sides, observed through the glass strips. If the swelling deformation keeps continuously stable for more than 48 h, the test can be stopped. The obtained results are depicted in Fig. 2.

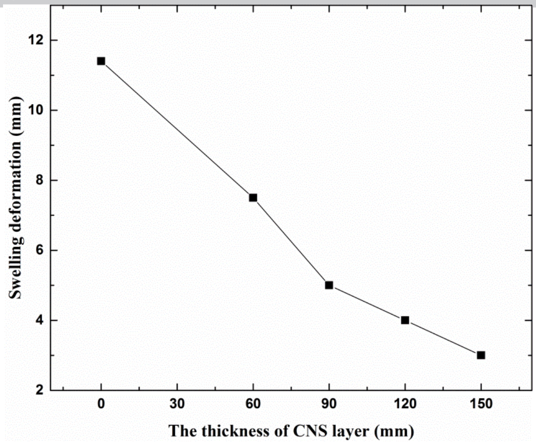

Fig. 2. The variation of swelling deformation of expansive soil in each model test.

It can be seen from Fig. 2 that the swelling deformation decreases as the thickness of the CNS layer increases. The corresponding swelling deformations for 0 mm and 60 mm of CNS surcharges are 11.4 mm and 7.5 mm, respectively. When the CNS surcharge over the expansive soil is increased to 90 mm, 120 mm and 150 mm, the swelling deformation does not exceed 5 mm. This means that the selected CNS material can effectively restrain the swelling characteristics of expansive soil, and the inhibition effect is positively correlated to the thickness of the CNS layer.

Fig. 3 shows the calculated and measured curves of swelling deformations. According to the definitions of swelling percentage and loaded swelling ratio (Section 2.4.3), they can be considered as the swelling potential of expansive soil, albeit the error of analytical method not being taken into account. The calculated swelling deformation is the product of the corresponding swelling percentage or loaded swelling ratio and soil layer thickness of 60 mm. It should be noted that the applied pressure for the loaded swelling ratio was set as the saturated weight of the given CNS layer in each laboratory model test, which means that the loaded swelling ratio is different when the thickness of the CNS layer changes. Therefore, the difference in the two calculated swelling deformations via swelling percentage and loaded swelling ratio may be a suitable method for evaluating the inhibition effect of CNS layer on the expansive soil. After measurement of the swelling percentage and loaded swelling ratio of expansive soil using the traditional oedometer, comparison of the above two calculated swelling deformations is illustrated in Fig. 3.

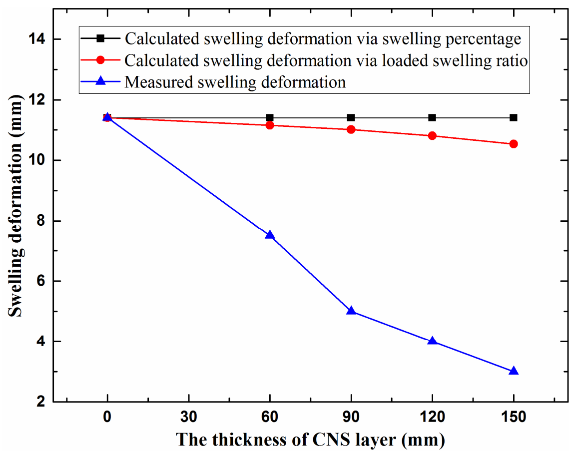

Fig. 3. Relationship between the measured and calculated swelling deformations.

It can be found in Fig. 3 that the deadweight of the CNS layer has a weak influence on the swelling characteristics of expansive soil based on the difference in the above two calculated swelling deformations. Even when the thickness of the CNS layer reaches 150 mm, the swelling deformation of expansive soil only reduces by 0.87 mm. However, the measured swelling deformation of expansive soil under various model tests reduces sharply with the increasing thickness of the CNS layer. These alterations are not only induced by the CNS deadweight, but also attributed to other factors. Previous attempts indicated that the key influence factor was likely the electrical charge effect caused by the cations aggregated in the saturation process (Katti et al., 1994; Murty and Praveen, 2008). For this, the inhibition effect of the electrical charge on the swelling characteristics of expansive soil is illustrated in Fig. 4.

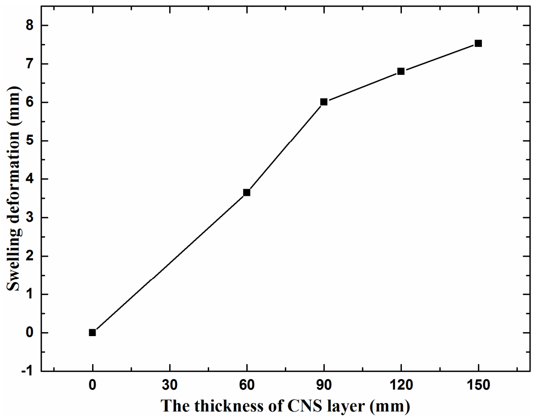

Fig. 4. Inhibition effect of electrical charges on the swelling deformation of expansive soil.

As can be observed from Fig. 4, the inhibition effect of the electrical charge on the swelling characteristics of expansive soil becomes more pronounced as the thickness of the CNS layer increases. The swelling deformations restrained by the electrical charge effect are 3.6 mm and 7.53 mm at the CNS thicknesses of 60 mm and 150 mm, respectively, whereas those inhibited by the deadweight of the CNS layer are only 0.26 mm and 0.87 mm, respectively (see Fig. 3). As such, it can be concluded that this electrical charge effect is 8–14 times the deadweight effect of the CNS layer.

3.2. Cation concentration of pore solution

Yao et al. (2004) pointed out that the main cations in the expansive soil in China are Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}, while K^{+} only accounts for approximately 2%–3% of the total cations. In the present work, the selected expansive soil and CNS mainly contained Ca^{2+} and Mg^{2+} (see Table 1). Therefore, the migration regulation of only Ca^{2+} and Mg^{2+} was assessed by measuring their concentrations in the pore solution of expansive soil and CNS layer during different test periods.

3.2.1. In the saturation process

In order to study whether the cations of the CNS layer migrate downward, accumulate, and form an electrical environment inside the expansive soil under unidirectional seepage, on the second day after water injection, the pore solution in the collection boxes was used to measure its ion concentration. Two model tests with CNS thicknesses of 90 mm and 150 mm, respectively, were considered, and the results are shown in Figs. 5 and 6, respectively.

It can be observed from Figs. 5 and 6 that the most widespread cation in the pore solution at the three layers is Ca^{2+}. The concentrations of Ca^{2+} and Mg^{2+} at the top of the CNS layer are the minimal and remain almost unchanged, while those at the CNS– expansive soil interface and bottom of expansive soil are maximal and decrease as the soil gradually reaches the saturation state.

According to Table 1, the concentrations of Mg^{2+} and Ca^{2+} in the pore solution of CNS layer are approximately twice and half those of expansive soil, respectively. However, when the tests started, the highest concentration of Mg^{2+} was observed at the CNS–expansive soil interface, the medium one is reported at the bottom of expansive soil, and the lowest was found at the top layer of CNS (see Figs. 5a and 6a). This result indicates that Mg^{2+} in the CNS layer migrates downward and then accumulates at the CNS–expansive soil interface and bottom of expansive soil after water injection, which makes the Mg^{2+} concentration at these areas higher than that at the top of the CNS layer. It can be seen from Figs. 5b and 6b that the highest concentration of Ca^{2+} is observed at the bottom of expansive soil, the medium one is at the CNS–expansive soil interface, whereas the lowest is observed at the top layer of CNS (well below half of that in the expansive soil). This phenomenon confirms that Ca^{2+} in the CNS layer also migrates downward in the saturation process and gathers at the CNS–expansive soil interface and bottom of expansive soil.

It can also be observed from Figs. 5 and 6 that the concentrations of Ca^{2+} and Mg^{2+} in the pore solution of expansive soil increase with the thickness of the CNS layer. In other words, cations in the CNS layer migrate down and are adsorbed on the surface of solids, and thus form an electrical environment inside the expansive soil under unidirectional seepage. Additionally, the concentration of cations that are accumulated in the expansive soil increases with the thickness of the CNS layer.

3.2.2. After the model test

This section aims to further verify whether the cations in the CNS and expansive soil layers migrate under unidirectional seepage. After the model test, soils at two layers, i.e. the top and bottom of the CNS and expansive soil, were sampled and dried at 105 °C to constant weight, then crushed and passed through to a standard 1-mm sieve. The concentrations of cations in the pore solution of soil samples were measured, as plotted in Fig. 7.

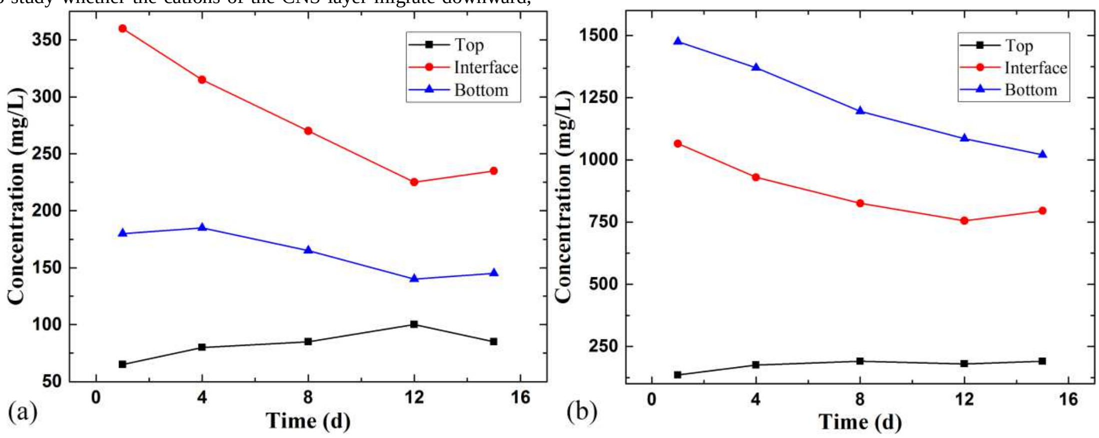

Fig. 5. Cation concentrations in the pore solution at three soil layers with CNS thickness of 90 mm: (a) Mg^{2+} and (b) Ca^{2+}.

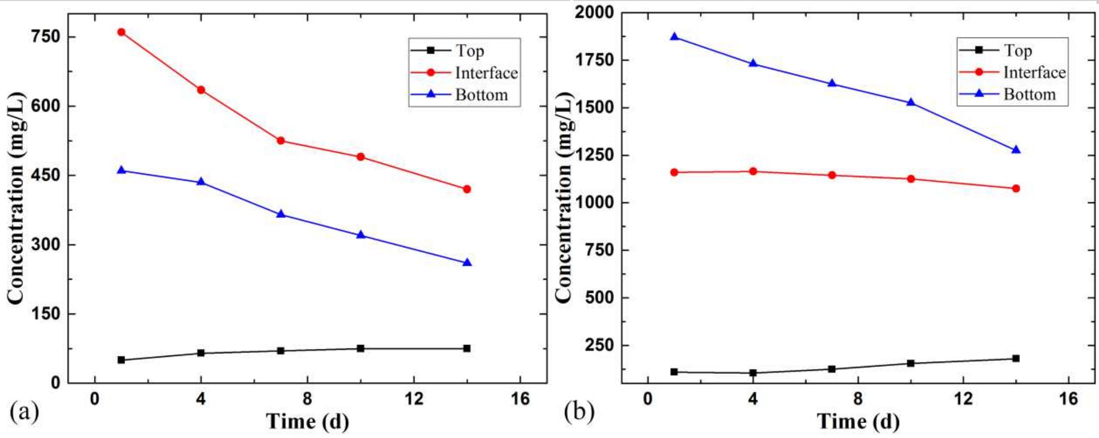

Fig. 6. Cation concentrations in the pore solution at three soil layers with CNS thickness of 150 mm: (a) Mg^{2+} and (b) Ca^{2+}.

As can be observed in Fig. 7, in comparison with the initial values (Table 1), the concentrations of Ca^{2+} and Mg^{2+} decrease in the CNS layer, but increase in the expansive soil. In addition, as the thickness of the CNS layer increases, the concentrations of Ca^{2+} and Mg^{2+} in the expansive soil layer also increase. The results show that Ca^{2+} and Mg^{2+} cations in the CNS layer move down, accompanied by a decrease in concentration under unidirectional water injection. Meanwhile, the migrated Ca^{2+} and Mg^{2+} cations accumulate on the surface of solids, and also form an electrical environment inside the expansive soil.

3.3. Swelling characteristics of expansive soil

The purpose of this section is to verify whether these Ca^{2+} and Mg^{2+} cations participate in the ionic exchange with the expansive soil. The modification effect of this exchange on the swelling potential of expansive soil can be evaluated by swelling tests. Therefore, after the model test, soils were sampled at the top and bottom of the expansive soil, and then dried and crushed to prepare for the swelling test based on the method mentioned in Section 2.4.3. It is should be noted that four parallel tests are required to determine each swelling index. The results are presented in Fig. 8.

As shown in Fig. 8, after completion of the model test, all swelling parameter values are lower than the initial ones, and the swelling potential of expansive soil is inversely proportional to the thickness of the CNS layer. This means that the swelling characteristics of expansive soil decrease irrevocably during the process of model test. It is noted that the saturated soil samples taken from the test apparatus are dried and wetted again to perform the swelling tests, and this drying-wetting process can also significantly affect the swelling characteristics of expansive soil. It is generally accepted that the swelling potential of expansive soil significantly reduces after the

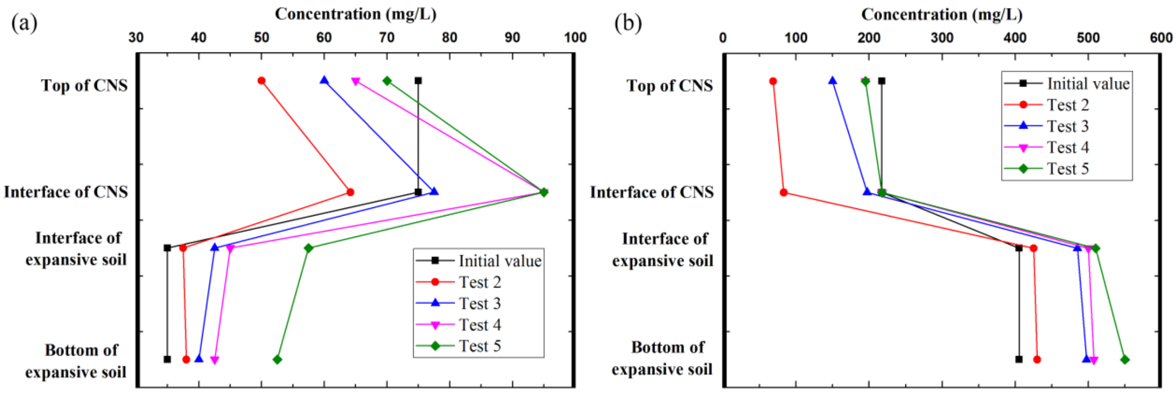

Fig. 7. Cation concentration in the pore solution at four soil interfaces after completion of the model test: (a) Mg^{2+} and (b) Ca^{2+}. Tests 2–5 refer to as the CNS layers with thicknesses of 60 mm, 90 mm, 120 mm and 150 mm, respectively.

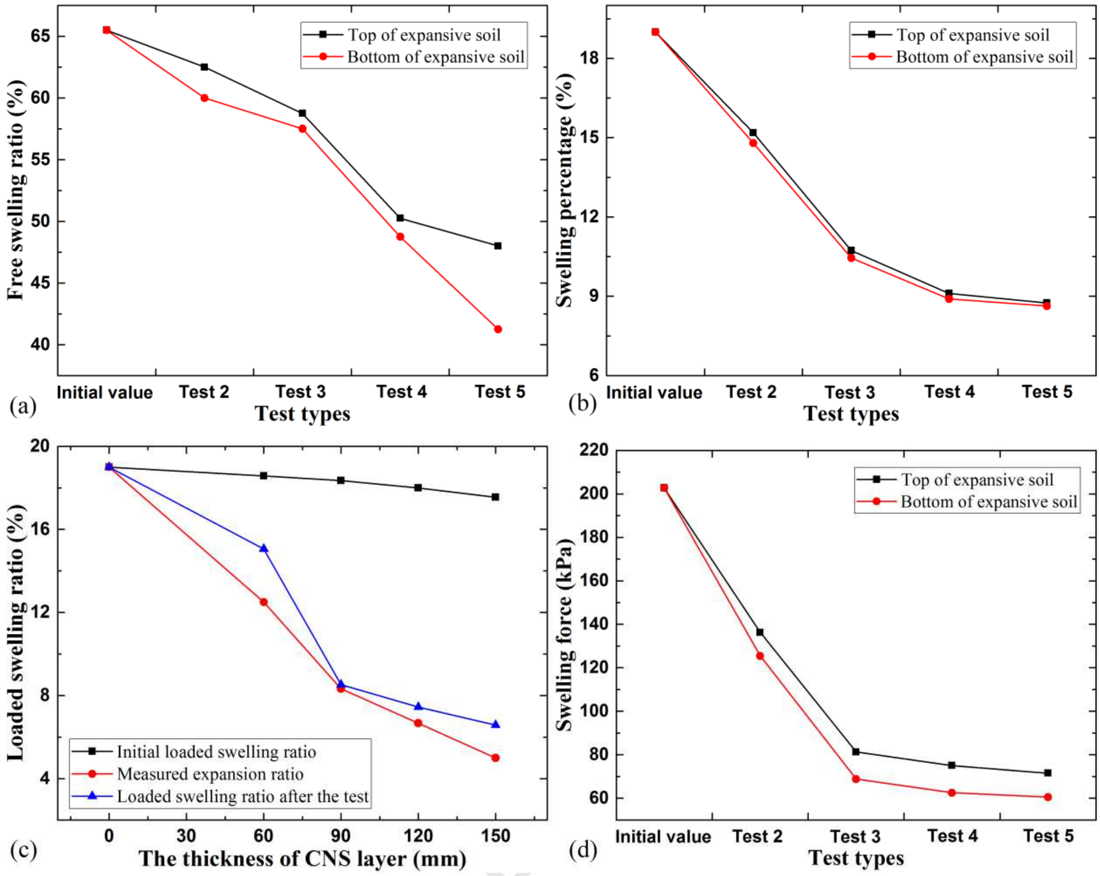

Fig. 8. Swelling characteristics of expansive soil: (a) free swelling ratio; (b) swelling percentage; (c) loaded swelling ratio; and (d) swelling force. Tests 2–5 refer to as the CNS layers with thicknesses of 60 mm, 90 mm, 120 mm and 150 mm, respectively.

drying-wetting cycle. However, the drying way has a market effect on the swelling characteristics of expansive soil (Basma et al., 1994). Popescu (1980), Osipov et al. (1987), Day (1994), and Rosenbalm and Zapata (2017) showed that when the soil sample is subjected to full drying, the expansive soil tends to have higher swelling potential as the number of drying-wetting cycle increases. In fact, the soil samples in this study were subjected to the full drying method. Therefore, the most reasonable explanation for the reduction in swelling potential is that the expansive soil has been changed because the cation exchange with the aggregating cations such as Ca^{2+} and Mg^{2+} leads to a decrease in the water-holding capacity of expansive soil.

Fig. 8c shows the evolution curves of the loaded swelling ratio of soil samples after model tests, compared with its initial values, along with the expansion ratio calculated via the measured swelling deformation in the five model tests. As shown in Fig. 8c, after model tests, the loaded swelling ratio of expansive soil is significantly lower than the initial value and is slightly higher than the measured expansion ratio. Meanwhile, it can be found in Fig. 8d that the swelling force still exceeds 60 kPa, which is greater than the deadweight of the CNS layer. The results indicate that the swelling behavior of expansive soil cannot be fully restrained by the modification effect. This may be due to the fact that the electrical environment inside the expansive soil formed by the migration and aggregation of cations makes some contributions (as described in Section 3.4). However, since all the soil samples of swelling tests were dealt in the de-ionized water rather than in the bulk solution, the electrical environment was destroyed, so that the swelling potential of expansive soil could only be partly restrained.

3.4. Inhibition mechanism of expansive soil by CNS layer

Based on the above analyses, the inhibition mechanism of expansive soil by the CNS layer can be attributed to the following aspects. Firstly, as shown in Fig. 9, under saturated condition of unidirectional water injection, the cations in the CNS layer migrate downward, and then are adsorbed on the surface of solids to form an electric environment inside the expansive soil. In this process, the adsorbed hydrated cations will participate in the ion exchange within the expansive soil, leading to the modification effect on the swelling potential of expansive soil. Besides, an adsorption water membrane is formed around the aggregates, accompanied by the crystalline swelling and diffuse double-layer (DDL) swelling (Norrish and Quirk, 1954; Liu, 2013), which leads to the reduction of porosity and collapse and reconstruction of soil skeleton under confined condition (Zhu et al., 2013). As the hydrated cations further migrate down, the aggregates continue to swell and split to occupy the micropores. At this time, the concentration of cations accumulated in the micropores will gradually increase, which in turn inhibits the development of DDL swelling of the aggregates until equilibrium is reached (Norrish and Quirk, 1954; Sridharan and Jayadeva, 1982). Devineau et al. (2006) pointed out that water molecules are more likely to be adsorbed in the interlayer space instead of in the micropores under confined conditions. Consequently, swelling of the aggregates is dominated by the crystalline swelling. However, Baver (1956) found that the inner layer of water molecules adsorbed on the surface of the aggregates may be in a solid water state and cannot move and exchange under the effect of Coulumb electrical field. Thus, it is difficult for external water molecules to enter the interlayer of montmorillonite crystals through the adsorbed water membrane. In

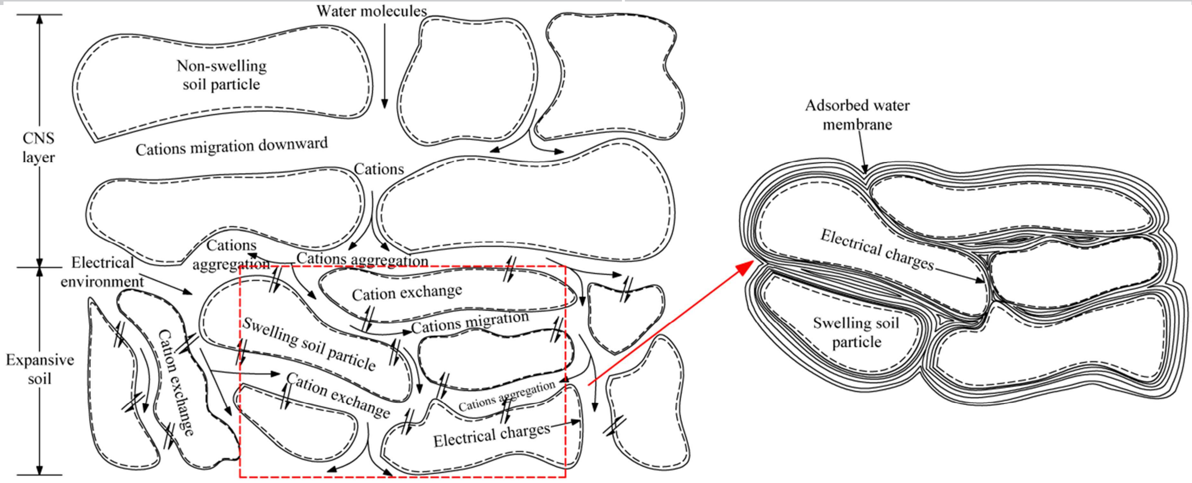

Fig. 9. Inhibition mechanism of expansive soil by CNS layer.

summary, under confinements, as the external cations migrate and aggregate, the later stages of swelling capacity of expansive soil are significantly inhibited.

Consequently, the joint effect of the modification effect and the electrical environment mainly controls the swelling characteristics of expansive soil, which can be considered as an electric charge effect. The main function of the CNS layer is, as an external factor, to prevent the expansive soil from expanding freely in the confined condition.

4. Conclusions

In the present work, the inhibition effect of a CNS layer on the swelling of expansive soil was investigated experimentally through five types of model tests under saturation condition of unidirectional water injection. The swelling inhibition mechanism of the CNS technology was discussed. The following conclusions can be obtained:

(1) Under saturated condition of unidirectional water injection, the fact that Ca^{2+} and Mg^{2+} cations in the CNS layer migrate downward, and then are adsorbed on the surface of solids to form an electric environment inside the expansive soil has been proved. Besides, the concentration of the aggregated cations in the expansive soil increases gradually with the thickness of the CNS layer.

(2) The CNS layer can effectively inhibit the swelling characteristics of expansive soil, and the inhibition effect becomes more remarkable as the thickness of the CNS layer increases. The swelling inhibition mechanism is the result of the joint action of three factors: (i) modification effect, (ii) electrical environment, and (iii) deadweight of the CNS layer. The joint contribution of the modification effect and electrical environment is 8–14 times higher than that of the deadweight effect of the CNS layer, and it can be concluded that electric charge effect mainly controls the swelling characteristics of expansive soil.

Conflict of interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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