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Research Article

Triaxial Mechanical Properties and Micromechanism of Calcareous Sand Modified by Nanoclay and Cement

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Calcareous sand is developed by the fracture of marine biological skeleton under the impact of seawater. Calcareous sand is not transported in the process of deposition. Therefore, calcareous sand retains the characteristics of marine biological skeleton, low strength, and porous. In order to study the effect of nanoclay and cement on the modification of calcareous sand, a series of tests were carried out on the modified cement calcareous sand (CCS) with different content of nanoclay. In this study, the triaxial mechanical properties and failure modes of nanoclay and cement composite modified calcareous sand (NCCS) were studied through the triaxial UU test. Then, SEM tests were carried out on CCS and NCCS samples, and the micromechanism of nanoclay and cement composite modified Nanhai calcareous sand was analyzed. The results showed that (1) the shear properties of CCS could be improved by adding nanoclay. The optimum admixture ratio of nanoclay was 8%, and its peak stress was 23%-39% higher than that of CCS. (2) The peak stress and strain of NCCS showed a linear correlation. (3) Compared with CCS, the internal friction angle and cohesion of NCCS were increased by 5.2% and 52%, respectively. (4) Nanoclay could improve the compactness and structure of cement calcareous sand, and the macroscopic performance is the improvement of peak stress and cohesion.

1. Introduction

Calcareous sand is the accumulation of pieces of carbonate materials, which are usually developed from shell fragments and skeletal debris of marine organism [1, 2]. Due to the fact that calcareous sand did not undergo long-distance transportation in the process of deposition [3], there are many small pores in calcareous sand particles with irregular shapes and large edges. In the 1960s and 1970s, the engineering properties of calcareous sand have received global focus at both the academic and the practical levels [4, 5]. After that, the basic engineering properties of calcareous sand have been paid more attention to studies [6]. The compressive properties of calcareous sand are similar to nanoclay, which is significantly affected by the particle breakage [7]. In terms of shear performance, the shear strength and plastic deformation of calcareous sand are larger than conventional terrigenous sand [8]. In addition, calcareous sand displays a larger internal friction angle than terrigenous sand [9, 10]. The shear performance of calcareous sand is mainly affected by its grain failure and dilatancy [11, 12]. The above studies have shown that the physical properties of calcareous sand are different from conventional terrigenous sand; it retains the characteristics of marine biological skeleton, low strength easy fragmentation, and high compressibility.

In practical engineering, a question arises herein as to whether some materials can be adopted to effectively reinforce the calcareous sand in order to make it meet the requirements of bearing capacity. At present, the improvement measures of calcareous sand mainly include cement reinforcement, polymer reinforcement, and MICP microbial induction reinforcement. Cement, as a common gelling agent, exhibits a good effect in strengthening soft soil [13–15]. Therefore, some scholars began to study the reinforcement effect of cement on calcareous sand. The cyclic triaxial test was carried out on cement calcareous sand by Sharma and Fahey [16], and they found that cement can improve the shear strength of calcareous sand. Ismail et al. [17]

Table 1: Basic physical indexes of calcareous sand in a certain area of Sansha City.

Sand depth/m	Gravity/$kN\cdot m^{-3}$	Cohesion/kPa	Internal friction angle/°	Compression modulus/MPa	Osmotic coefficient/$cm\cdot s^{-1}$	Bearing capacity/kPa
25~30	18	5	30	10	8.0×10^{-2}	200

Table 2: Basic physical and mechanical indexes of cement.

Fineness/%	Initial setting time/min	Final setting time/min	Loss on ignition/%	Compressive strength/MPa		Flexural strength/MPa	
				3 d	28 d	3 d	28 d
3.4	210	295	1.4	26.9	48.1	4.9	9.0

Table 3: Technical indexes of nanoclay.

Components	Appearance	Montmorillonite content/%	Apparent density (g/cm^3)	Radius-thickness ratio	Layer thickness/nm	Moisture content/%
Montmorillonite derivatives	Light pink powder	96-98	0.45	200	≤25	≤3

studied the influence of different cementitious materials on calcareous soil shear performance via triaxial test, and the result showed that compared with calcite powder and gypsum powder, the cementation degree of silicate cement to calciferous sand was better. Wang et al. [18] studied the effect of cement content on the shear performance of calcareous sand through the triaxial test, and the result showed that the addition of cement could improve the shear strength of calcareous sand. The modification effect is optimal when the content of cement is 15%, and compared with ordinary calcareous sand, the strength is 1.7 times.

As the most promising material in the 21st century, nanomaterials have been widely used in various fields due to its excellent properties [19–22]. Gao and coworkers [23, 24] explored the influence of nano-MgO on the mechanical performance of soft clay via an unconfined compression test, and the research indicated that the engineering properties of soft clay could be improved by adding an appropriate amount of nano-MgO. Wang et al. [25] found that nano-MgO can modify the shear performance of cement silty clay through the direct shear test, and the optimal blending ratio is 5‰. As a common nanomaterial, nanoclay is also widely used in improving the performance of cement-based materials. An unconfined compression test for exploring the effect of nanoclay on the compressive properties of cement iron tailings is reported by Li et al. [26], and the result showed that the compressive property of cement iron tailing sand can be improved by adding 5%–10% nanoclay instead of cement. Zaid et al. [27] conducted the unconfined compression test on solidified soft soil with nanoclay and nano-CuO, respectively, and the result showed that the effect of nanoclay-cured soft soil was significantly better than that of nano-CuO. Li et al. [28] explored the effect of nanoclay on the shear performance of soft clay through the direct shear test, and the result showed that the addition of nanomontmorillonite can increase the shear strength and internal friction angle of the clay. Wang et al. [29] research showed that nanoclay could

Table 4: Experimental design scheme.

Sample no.	Cement content/%	Nanoclay content/%	Water content/%	Curing age/d
CCS	10	0	30	7
NCCS-4	10	4	30	7
NCCS-6	10	6	30	7
NCCS-8	10	8	30	7
NCCS-10	10	10	30	7

effectively improve the compressive properties of cement calcareous sand. Overall, nanoclay can improve the mechanical performance of soft soil and cement-based materials.

In spite of a lot of reports have explored the mechanical performance of nanoclay solidified soft soil and cement-based materials, there are still few researches on mechanical performance of calciferous sand modified by nanomaterial and cement composite. Therefore, with the aim of addressing the above concerns, a systematic laboratory program was carried out to explore the effect of nanoclay content and confining pressure on the shear performance of CCS. And the SEM was used to analyze the micromechanism of NCCS. We hoped that the outcomes of this study will not only provide convincing evidence on the role of nanoclay in a mixture, but can also serve as a useful reference for engineering applications of NCCS in offshore engineering and for relevant theoretical developments.

2. Materials and Sample Preparation

2.1. Materials. In this test, the loose and unconsolidated calcareous sand was taken from an area of Yongxing Island,

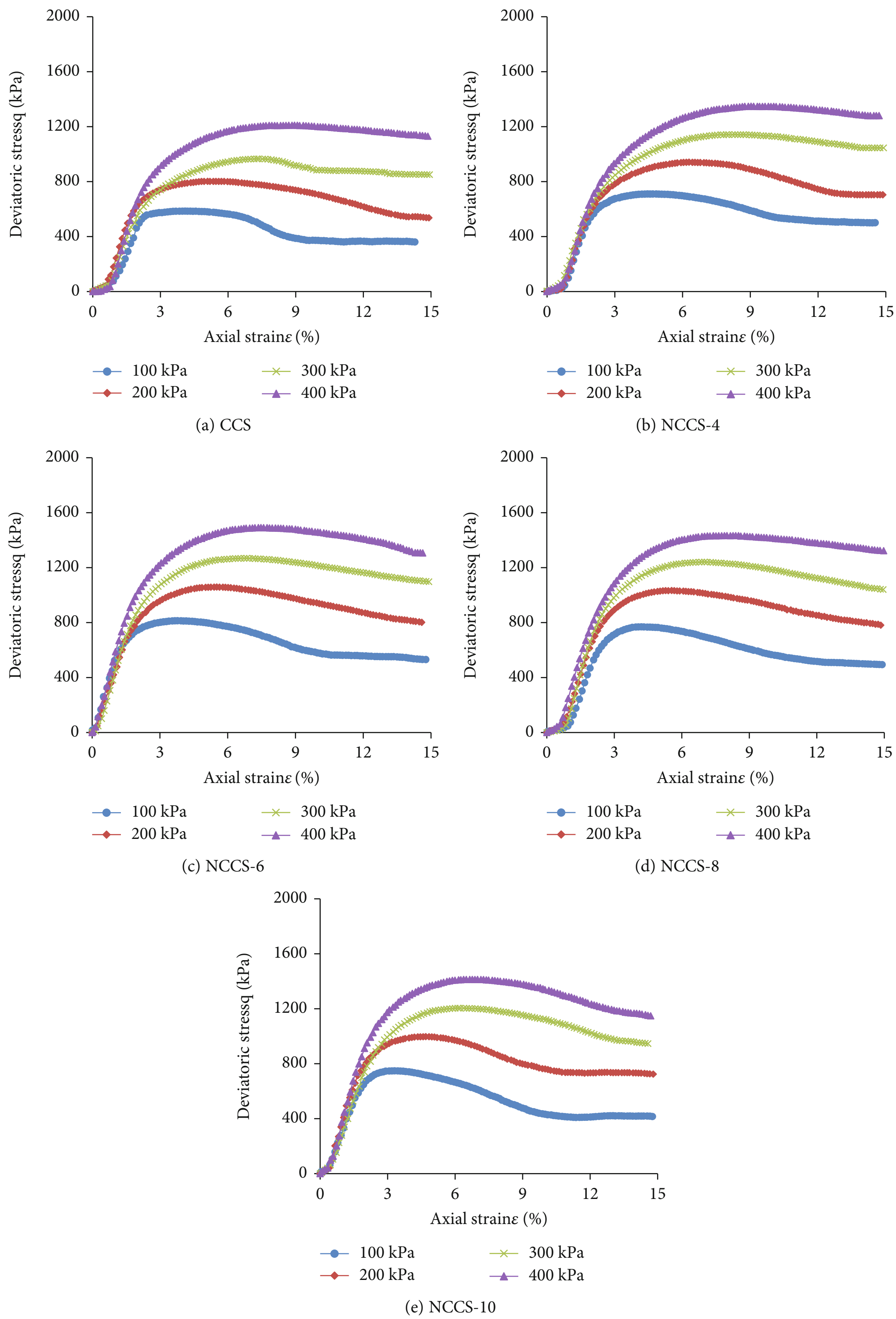

Figure 1: Stress-strain curves of CCS and NCCS.

Sansha City, Hainan Province. It generally showed white; meanwhile, red particles are present in calciferous sand due to the presence of coral debris. To remove any possible influence of particle size and grading, sieved calcareous sand (0.25-1 mm) was adopted as the base sand; all particle size is less than 2 mm. Basic mechanical indexes of calcareous sand are shown in Table 1. The cement used in the test was Lanting PO 32.5 ordinary silicate cement produced by Shaoxing Zhaoshan Building Materials Co., Ltd.; the basic physical mechanical indexes are shown in Table 2. Nanoclay is a faint yellow powder, produced by Hubei gold fine montmorillonite technology Co., Ltd, and its main technical indicators are shown in Table 3.

2.2. Experimental

2.2.1. Instrument. TKA-TTS-3S was used for the triaxial shear test, which was produced by Nanjing Texao Technology Co., Ltd. In this study, the unconsolidated and undrained (UU) test was performed on calcareous sand to investigate the effects of different confining pressure, such as 100, 200, 300, and 400 kPa, on NCCS shear performance. According to GBT 50123-2019 Geotechnical Test Standard [30], the shear rate of the specimen is set at 0.6 mm/min, and the test is stopped when the axial strain reaches 15%.

2.2.2. Experimental Scheme. Considering the effect of nanoclay content on the shear performance of CCS, cement content at 10% and water content at 30% were controlled in the test to explore the effects of different nanoclay content and confining pressure on triaxial shear properties of CCS. The experimental design is shown in Table 4.

2.3. Sample Preparation and Curing. According to the "GBT 50123-2019 Geotechnical Test Standard," the triaxial specimens in this test were all cylinders with diameter $D = 39.1$ mm and height $H = 80$ mm. Before the test, the dried calcareous sand was sieved through a 2 mm sieve to remove impurities such as small and medium shells and coral debris. The calcareous sand sample was compacted in 4 layers, 41 g of the calcareous sand mixed sand sample was weighed at each time. After each layer of compaction was completed, the surface of the calcareous sand sample needed to be roughened to ensure the internal integrity of the sample. Then the as-acquired sample was placed into a three-valve saturation device, and filter stones were placed at both ends of the sample; the filter paper was required to be placed between the filter stones and the sample to prevent calcareous sand particles from adhering to the filter stones. Due to the loose and non-caking characteristics of calcareous sand, the specimens needed to be maintained with a matrix for 4 days and then removed the matrix. Finally, the as-obtained sample was put into a curing room for curing.

3. Triaxial UU Test

3.1. Stress-Strain Curves. The effect of nanoclay content on the shear performance of CCS was explored in this test. Four confining pressures of 100, 200, 300, and 400 kPa were all test for four NCCS samples (0, 4%, 6%, 8%, and 10%). The stress-strain curves of NCCS with different nanoclay content were shown in Figure 1.

In Figure 1, the stress-strain curves of CCS and NCCS showed softening curves. The deviatoric stress showed a slight decrease after peak stress occurred in the CCS samples. When the confining pressure was from 400 kPa to 100 kPa,

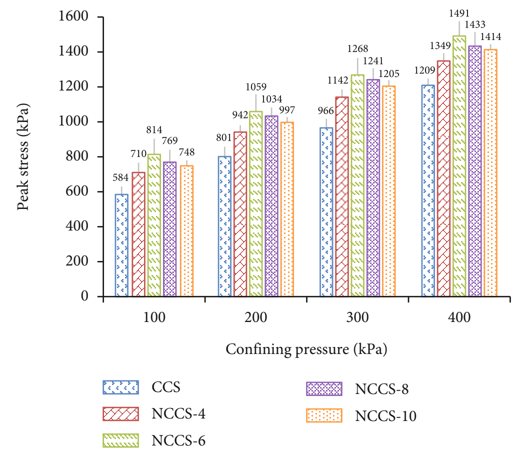

Figure 2: Relation of nanoclay content and peak stress of NCCS.

Table 5: Peak strain of CCS and NCCS (%).

Nanoclay content/%	Confining pressure/kPa			
	100	200	300	400
0	3.67	4.82	7.27	7.82
4	4.45	6.29	7.71	9.03
6	3.78	5.52	6.84	7.48
8	4.20	5.55	7.01	8.01
10	3.31	4.70	6.12	6.65

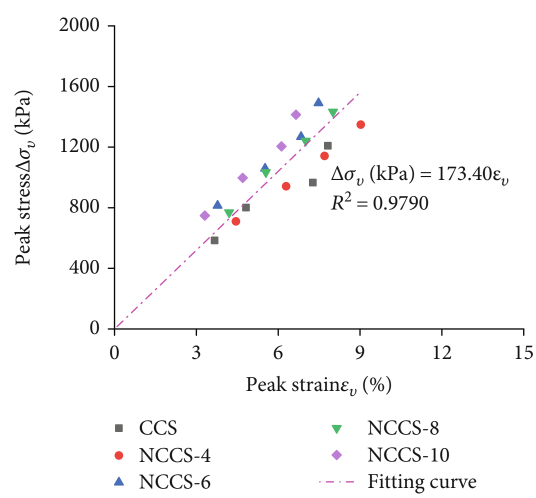

Figure 3: Relation of peak stress and peak strain of NCCS.

the softening trend of the stress-strain curves of CCS gradually increased. With the increase of nanoclay content, the softening trend of stress-strain curves of NCCS was gradually obvious.

3.2. Effects of Nanoclay Content on Peak Stress of NCCS. Peak stress was the maximum deviatoric stress in the deviatoric stress-strain curve. Figure 2 showed the relation of nanoclay content and peak stress of NCCS.

As shown in Figure 2, the addition of nanoclay could improve the peak stress of CCS. When the confining pressure

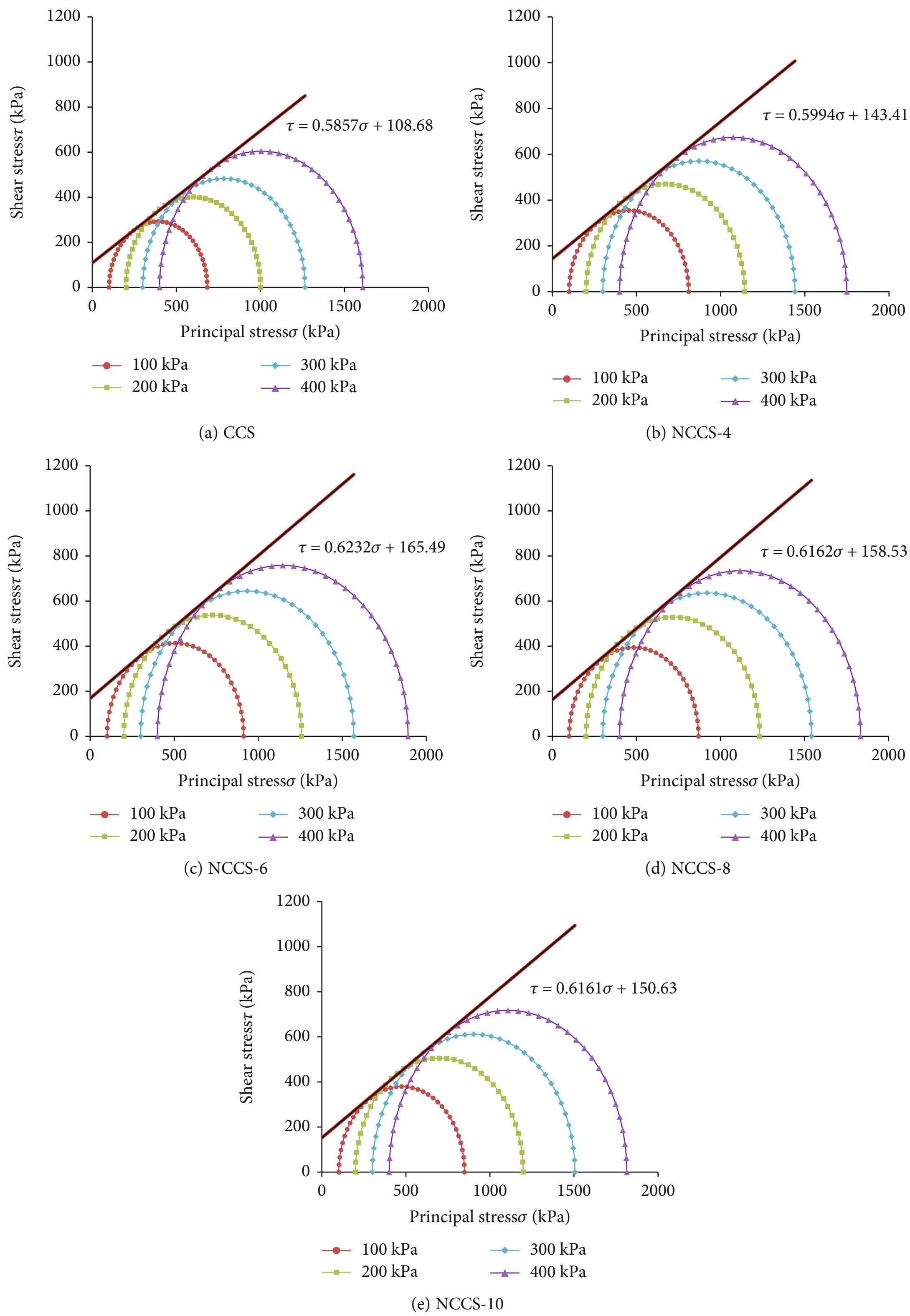

Figure 4: Strength envelopes of CCS and NCCS.

was within the range of 100 kPa to 400 kPa, the corresponding peak stress of CCS was 584 kPa, 801 kPa, 966 kPa, and 1209 kPa, respectively. Compared with CCS, the peak stress of NCCS-4, NCCS-6, NCCS-8, and NCCS-10 was increased by 12%–22%, 23%–39%, 19%–32%, and 17%–28%, respectively. Under the same confining pressure, the above data also indicated that with the increase of nanoclay content, the peak stress of NCCS increased first and then decreased.

In summary, the optimized nanoclay content of NCCS was 6%, and its peak stress was 23%–39% higher than CCS.

3.3. Peak Strain of NCCS. Table 5 lists peak strains CCS and NCCS.

As shown in Table 1, the peak strain of NCCS exhibited smaller under the smaller confining pressure. When the confining pressure increased, the peak strain of NCCS increased, indicating that NCCS had good ductility under the constraint of higher confining pressure. The peak strain and peak stress of NCCS with different content of nanoclay were compared. As shown in Figure 3, the peak stress and peak strain of NCCS were basically linear.

3.4. Shear Strength Index of NCCS. To further study the modification effect of nanoclay on CCS shear strength, the strength envelops of CCS and NCCS were drawn according to the Mohr-Coulomb theory, and the shear strength c and φ were obtained. The ultimate stress circle of CCS and NCCS under different confining pressure was shown in Figure 4.

As shown in Figure 4, when CCS and NCCS samples were in failure models, with the increase of the effective confining pressure, the diameter of the stress circle would gradually increase and the strength envelop presented a diagonal line, which was similar to the conclusion of cement soil research [31]. Du et al. [32] pointed out that in the triaxial UU test, the low saturation state of the sample would make the strength and confining pressure linearly increase. The reason mainly had the following two aspects; on the one hand, the initial water content of the CCS and NCCS samples was lower than the saturated water content. On the other hand, the hydration reaction of cement consumed water in the CCS and NCCS samples during curing. These two reasons caused both the CCS and NCCS samples to be in a low saturation state. Therefore, the existence of initial confining pressure would cause isotropic compression and the decrease of void ratio of the CCS and NCCS samples. With the increase of the confirmation pressure, the strength of the sample increased and the increment of pore pressure decreased [33]. In the process of shear failure, the effective stress of CCS and NCCS samples increased step by step as the confining pressure increased from 100 kPa to 400 kPa. It was further clarified that the diameter of the stress circle of CCS and NCCS will also increase. Therefore, different from the conventional soft soil triaxial UU test, the strength envelope of CCS and NCCS showed an obvious diagonal line, that is to say, the value of internal friction angle would be much greater than 0. This result indicated that the mechanical performance can be effectively improved by the addition of cement and nanoclay to calcareous sand.

Figure 5 showed the relation of nanoclay content and internal friction angle of NCCS. As exhibited in Figure 5, the internal friction angle of CCS was 30.36°, which was 0.36° higher than that of calcareous sand, indicating that the incorporation of cement has little effect on calcareous sand internal friction angle. The internal friction angle of NCCS-4, NCCS-6, NCCS-8, and NCCS-10 was 30.94, 31.93, 31.64, and 31.63, respectively, which was 1.9%, 5.2%, 4.2%, and 4.2% higher than CCS, indicating that nanoclay

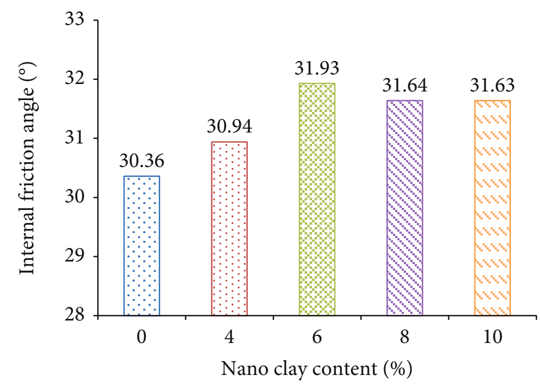

Figure 5: Relation of nanoclay content and internal friction angle of NCCS.

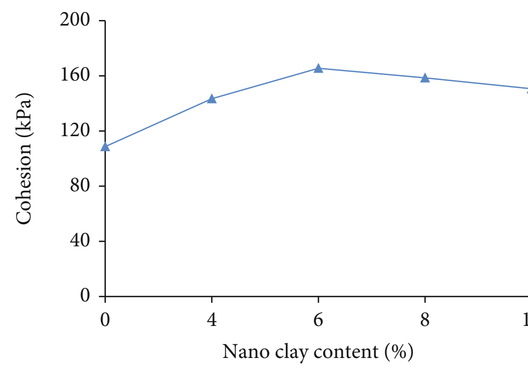

Figure 6: Relationship between nanoclay content and NCCS's cohesion.

can rapidly increase the internal friction angle of NCCS when the content of nanoclay was small. When there was more nanoclay content, the increase of internal friction angle of NCCS tends to be gentle, even decreased. Therefore, for NCCS, with the increase of nanoclay content, the internal friction angle of NCCS generally increased first and then decreased; when the nanoclay content was 6%, the internal friction angle of NCCS reached maximum value, it increased by 5.2% compared with that of CCS.

Figure 6 showed the relation of nanoclay content and NCCS cohesion. According to Figure 6, the cohesion of CCS was 108.68 kPa, indicating that the incorporation of cement can significantly improve the cohesion of calcareous sand. The cohesion of CCS was further improved by the modification of nanoclay. The cohesion values for NCCS-4, NCCS-6, NCCS-8, and NCCS-10 were 143.41, 165.49, 158.53, and 150.63 kPa, respectively, 32%, 52%, 46%, and 39% higher than the cohesion of CCS values, respectively. Therefore, the incorporation of nanoclay could improve the cohesion of CCS. With the increase of nanoclay content, the cohesion of NCCS increased firstly and then decreased. When nanoclay content was 6%, cohesion of NCCS was the best value, which was 52% higher than CCS.

In summary, the modification of nanoclay could improve the shear properties of CCS. When nanoclay content was 6%, the internal friction angle and cohesion of NCCS reached the

(a) CCS (b) NCCS

Figure 7: Failure characteristics of specimens.

maximum. In this case, cohesion of NCCS was 52% higher than CCS, while the internal friction angle was 5.2% higher than CCS. Therefore, the shear performance of NCCS was mainly achieved by enhancing the cohesion of CCS. The modification of nanoclay could improve the bite force between the particles in calcareous sand, while it was little effect on the internal friction of NCCS. The reason that nanoclay could improve the shear strength index of CCS can be attributed to: calcareous sand was loose sand particles with low cohesion, but the cementitious material produced by the hydration reaction of cement could increase the cohesive force between sand particles. The nanoclay particles were small and highly active, which could not only absorb water and expand to fill the pores but also promote the hydration reaction of cement and increase the production of cementitious substances. These two aspects could improve the bite force between sand particles, so as to improve the shear strength index of CCS.

3.5. Failure Characteristics. In order to deeply study the effect of nanoclay incorporation on the failure mode of CCS, the failure modes of CCS and NCCS samples were analyzed when the confining pressure was 300 kPa, as shown in Figure 7.

As depicted in Figure 7, CCS was drum-like failure in the middle without obvious cracks, while NCCS was inclined fracture failure. This may be due to the large number of pores in CCS, which had high compressibility under the constraint of certain confining pressure. After modified by nanoclay, the pores in NCCS were decreased and its compressibility was decreased, so that NCCS presented oblique inclined fracture failure.

4. Micromechanism

In order to investigate the micromechanism of shear performances of calcareous sand modified by nanoclay and cement, cement calcareous sand (CCS) and nanoclay-cement calcareous sand (NCCS) were characterized by scanning electron microscope. The microscopic features of CCS and NCCS were shown in Figures 7 and 8, respectively.

As depicted in Figure 8, the fibrous and flocculent water-insoluble gelling substances (C-S-H) were distributed in the spindle-shaped pores on the surface of calcareous sand, which indicated that the generation of hydration products can bond calcareous sand particles better. Meanwhile, the small particles of calcareous sand broken during the test also filled the pores of the larger particles of calcareous sand. As shown in Figure 9, there were many fine nanoclay particles and few plate-like massive substances in the microstructure of NCCS. The distribution of fine particles was irregular on the structural plane. And in addition, fibrous hydration products were generated between the particles of calcareous sand. Compared with CCS, the pores in the microstructure of NCCS were significantly reduced, and a relatively complete bulk structure appeared, indicating that the modification of nanoclay can improve the compactness of CCS. At macro level, the shear strength of NCCS increased.

There were two reasons why nanoclay modification can change the shear performance of CCS. On the one hand, the particle size of nanoclay was small, while the surface of calciferous sand had lots of spindle-shaped pores, thus, nanoclay could improve the shear strength of CCS by filling the pores on the surface of calciferous sand. On the other hand, nanoclay possesses a nucleation effect. Nanoclay could

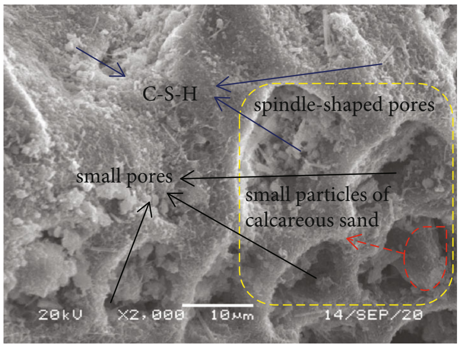

Figure 8: Microscopic features of CCS.

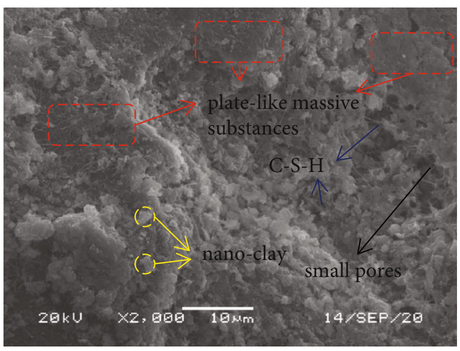

Figure 9: Microscopic features of NCCS.

adsorb free Ca ions in NCCS samples and promote the hydration reaction of cement in NCCS. To summarize, the modification of nanoclay could improve the compressibility and structure of NCCS, which further improves the shear strength of CCS.

5. Conclusions

The triaxial mechanical properties and micromechanism of CCS and NCCS with water content of 30% and cement content of 10% were investigated via triaxial UU shear tests. The following conclusions can be drawn:

(1) The stress-strain curves of both CCS and NCCS were softening curves

(2) The modification of nanoclay can improve the shear properties of the CCS. The optimum content of nanoclay is 6%, and its peak stress was 23% ~39% higher than CCS. Meanwhile, the cohesion of NCCS increased by 52% compared with CCS, and the internal friction angle increased by 5.2%

(3) NCCS exhibited good ductility under high confining pressure, and the peak deviatoric stress of NCCS with different content of nanoclay had a linear correlation with peak strain

(4) CCS was drum-like failure in the middle without obvious cracks, while NCCS was inclined fracture failure

(5) Due to the filling effect and nucleation effect, the modification of nanoclay could improve the compactness and structure of CCS, and the macroscopic performance was the improvement of peak stress and cohesion

Data Availability

All the data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

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