

Article

Mechanical Properties and Micro Mechanism of Nano-Clay-Modified Soil Cement Reinforced by Recycled Sand

Biao Qian, Wenjie Yu, Beifeng Lv, Haibo Kang *, Longxin Shu, Na Li * and Wei Wang 

School of Civil Engineering, Shaoxing University, Shaoxing 312000, China; Qianbusx@163.com (B.Q.); 19020852080@usx.edu.cn (W.Y.); 20020852047@usx.edu.cn (B.L.); shulongxin1027@163.com (L.S.); wellswang@usx.edu.cn (W.W.)

* Correspondence: 18020852079@usx.edu.cn (H.K.); lina@usx.edu.cn (N.L.)

Abstract: To observe the effect of recycled sand and nano-clay on the improvement of the early strength of soil-cement (7d), 0%, 10%, 15% and 20% recycled sand were added. While maintaining a fixed moisture content of 30%, the ratios of each material are specified in terms of soil mass percentage. The shear strength of CSR (recycled sand blended soil-cement) was investigated by direct shear test and four groups of specimens (CSR-1, CSR-2, CSR-3 and CSR-4) were obtained. In addition, 8% nano-clay was added to four CSR groups to obtain the four groups of CSRN-1, CSRN-2, CSRN-3 and CSRN-4 (soil-cement mixed with recycled sand and nano-clay), which were also subjected to direct shear tests. A detailed analysis of the modification mechanism of soil-cement by recycled sand and nano-clay was carried out in combination with scanning electron microscopy (SEM) and IPP (ImagePro-Plus) software. The test results showed that: (1) CSR-3 has the highest shear strength due to the “concrete-like” effect of the incorporation of recycled sand. With the addition of 8% nano-clay, the overall shear strength of the cement was improved, with CSRN-2 having the best shear strength, thanks to the filling effect of the nano-clay and its high volcanic ash content. (2) When recycled sand and nano-clay were added to soil-cement, the improvement in shear strength was manifested in a more reasonable macroscopic internal structure distribution of soil-cement. (3) SEM test results showed that the shear strength was negatively correlated with the void ratio of its microstructure. The smaller the void ratio, the greater the shear strength. This shows that the use of reclaimed sand can improve the sustainable development of the environment, and at the same time, the new material of nano-clay has potential application value.



Citation: Qian, B.; Yu, W.; Lv, B.; Kang, H.; Shu, L.; Li, N.; Wang, W. Mechanical Properties and Micro Mechanism of Nano-Clay-Modified Soil Cement Reinforced by Recycled Sand. *Sustainability* **2021**, *13*, 7758. <https://doi.org/10.3390/su13147758>

Academic Editors: Chunjiang An and Christophe Guy

Received: 5 June 2021

Accepted: 7 July 2021

Published: 12 July 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: recycled sand; nano-clay; soil-cement; mechanical properties; micro mechanism; sustainable

1. Introduction

In recent years, soil-cement has been widely used in foundation reinforcement, pavement bed courses, foundation anti-seepage, supporting structures and other projects to improve the strength performance and structural integrity of soil [1–3]. However, the production of cement consumes a lot of energy and causes considerable pollution to the environment [4,5]. Therefore, for the purpose of controlling cement consumption and improving soil strength, adding a small amount of additives and appropriately replacing cement with another environmentally friendly material is a very promising approach. Among them, recycled sand is a feasible alternative material.

Recycled sand is a kind of recycled material obtained by crushing construction waste. Its background is the rapid explosion of construction waste [6,7]. The generation of construction waste means that a large amount of natural resources need to be consumed to build new buildings. The improper disposal of construction waste will also take up a lot of space. Therefore, the secondary or even multiple use of abandoned buildings in the form of recycled sand can not only reduce the dependence on natural resources to a certain extent, but also strengthen the treatment of waste, while, at the same time, also being able

to improve the sustainable development of the environment. However, although replacing part of the cement with recycled sand can maintain the strength of soil-cement, recycled sand is a kind of harder material that has a physical interaction with soil and does not have a chemical interaction between cement and soil. Therefore, in order to seek better modification effects, one option is to add nanocomposite recycled sand into soil-cement.

Nanomaterials are the products of nanotechnology development, which have been used in the fields of chemistry and medicine [8,9]. Soil improvement research is also involved [10–12]. For example, nano-magnesium oxide, nano-titanium dioxide, nano-carbon tubes, nano-clay, graphene oxide, and various nano-sized fillers or additives are added to soil as well as soil-cement. The improvement of soil-cement admixed with nanomaterials can be attributed to three aspects: (1) Nanomaterials have higher surface energy [13,14], which can accelerate the hydration reaction of cement; (2) Nano-sized particles of nanomaterials can cause changes in physical aspects, resulting in filling effects and further improvement in packing density [15–17]; (3) Nucleation effect, that is, the product of the hydration reaction encloses the soil particles to form a denser matrix [18,19]. Among various nanomaterials, nano-clay is a better nanomaterial [20–23], which not only has a low production cost, but also has a better modification effect. Bahari et al. [24] studied the stabilization effect of nano-clay with content of 0.5%, 1%, 1.5% and 2% of the original soil mass on silty soil, and analyzed the improvement effect of nano-clay on the geotechnical properties of stabilized silty soil. The results showed that the cohesion and internal friction angle were significantly improved with the increase in nano-clay content, which indicated that nano-clay could significantly improve the shear strength of soil. In summary, although many researchers have independently studied the modification effects of the two building materials, recycled sand and nano-clay, the effects of incorporating the composites of these two materials into soil-cement on soil behavior have been neglected. Therefore, in recognition of the lack of information on the effectiveness of recycled sand and nano-clay in the reinforcement of soil-cement, it was decided to make this highly relevant area of study the main objective of the current study. It is foreseeable that recycled sand and nano-clay will have considerable improvement effects on soil-cement.

In this study, an appropriate amount of recycled sand and nano-clay were added to soil-cement, and their modification effects on the shear strength of soil-cement through direct shear tests were compared. The specific action mechanism was discussed by means of SEM microscopic tests, with a view to revealing the sustainable development value of reclaimed sand and the mechanism of interaction with new nanomaterials, providing a reference for engineering construction in coastal areas.

2. Test Materials and Methods

2.1. Test Materials

The soil used throughout this test was coastal soft soil collected from Shaoxing, Zhejiang, China. As shown in Figure 1a, it is brown-yellow. The specific physical properties are shown in Table 1, and the SEM microstructure diagram is shown in Figure 1b. The M 32.5 cement used in this test was produced by Zhuji Conch Cement Company (Zhejiang, China); it is a substitute for PC 32.5 cement after its cancellation, and its strength is the same as PC 32.5 cement. Its basic indexes are shown in Table 2, and the SEM microstructure diagram is shown in Figure 1d. Recycled sand is made from the broken concrete of demolished frame structures. These concretes are originally construction waste, piled together forming a high potential energy slope, which has a risk of instability and sliding. After crushing and processing in the factory, part of the products is recycled sand. The gradation of used recycled sand is shown in Table 3, which is produced by Shanghai Youhong Environmental Technology Co., Ltd. (Shanghai, China), as shown in Figure 1e. The SEM microstructure diagram is shown in Figure 1f: its water absorption is less than 3.0%, its apparent density is more than 2450 kg/m³, and its porosity is less than 47%. The nano-clay used throughout this test was produced by Hubei Gold Fine Montmorillonite Technology Co., Ltd. (Hubei, China). It is a light pink powder, as shown in Figure 1g;

the SEM microstructure diagram is shown in Figure 1h, and the chemical compositions of M32.5, recycled sand and nano-clay are shown in Table 4.

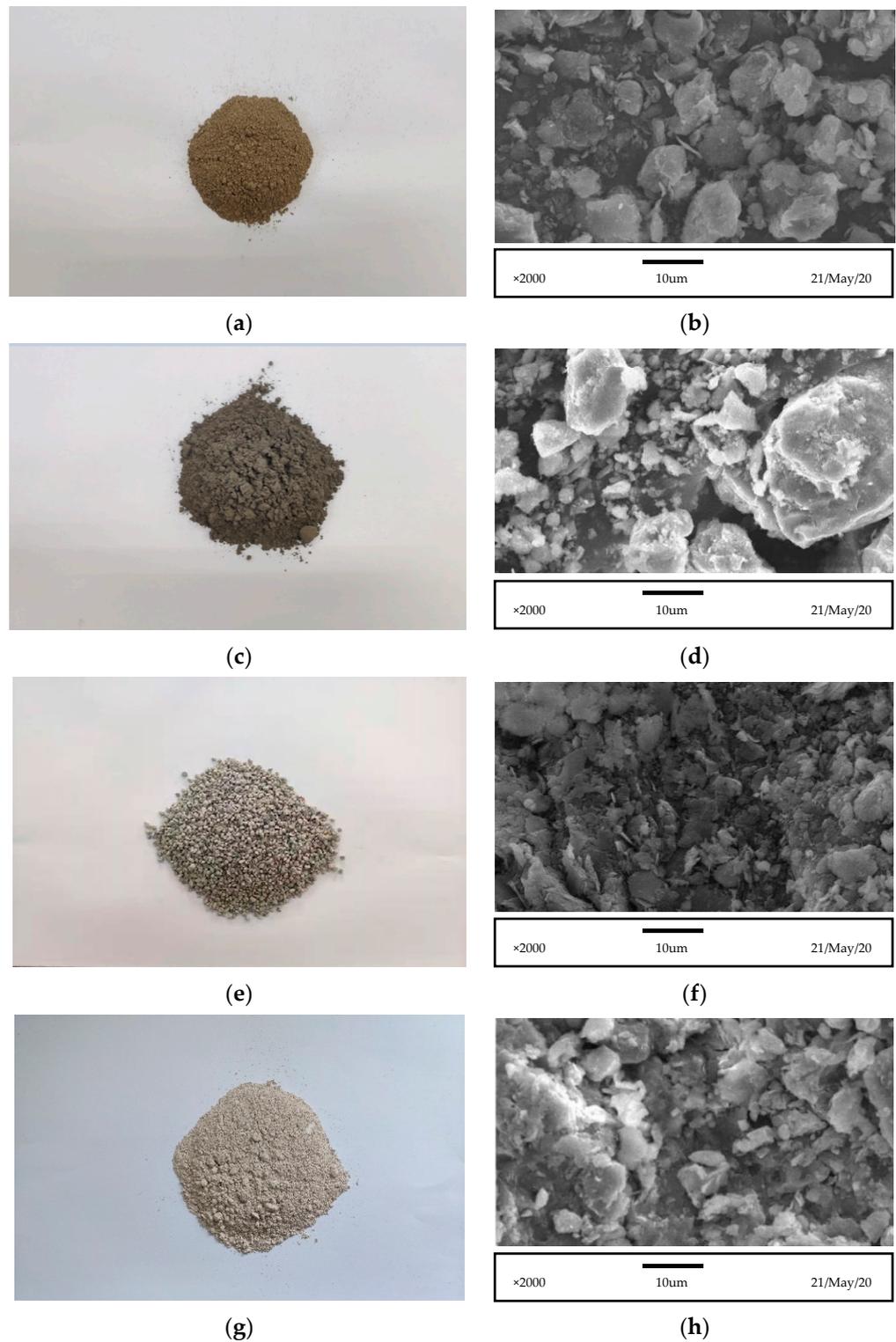


Figure 1. Coastal soft soil (a) and SEM (b), Soil-cement (c) and SEM (d), recycled sand (e) and SEM (f), Nano-clay (g) and SEM (h).

Table 1. Physical properties indexes of subgrade soil [25].

Density	Pore Ratio	Water Content (%)	Liquid Limit (%)	Plastic Limit (%)	Liquidity Index	Plastic Index
1.65	1.64	30.0	46.2	26.4	1.7	19.8

Table 2. Basic indexes of M32.5 cement.

Setting Time (min)		Flexural Strength (MPa)		Bending Strength (MPa)	
Initial Set	Final Set	3 d	28 d	3 d	28 d
≥60	≤720	≥2.5	≥5.5	≥10	≥32.5

Table 3. Gradation of recycled sand.

d/mm	$2 \geq d \geq 0.074$	$3 \geq d > 2$
P/%	70	30

Table 4. Chemical composition of M32.5, recycled sand and nano-clay.

Materials	Chemical Composition									
M32.5	CaO (%)	SiO ₂ (%)	Al ₂ O ₃ (%)	Fe ₂ O ₃ (%)	SO ₃ (%)	MgO (%)	Others (%)			
	64.05	21.30	6.09	3.08	1.76	1.21	2.51			
Recycled sand	SiO ₂ (%)	Al ₂ O ₃ (%)	Na ₂ O (%)	K ₂ O (%)	Fe ₂ O ₃ (%)	CaO (%)	MgO (%)	TiO ₂ (%)	SiO ₃ (%)	Others (%)
	54.37	12.90	2.78	1.68	8.28	7.94	4.07	1.44	0.24	0.52
Nano-clay	Montmorillonite %			Arsenic mg/kg		Lead mg/kg		Mercury mg/kg		Cadmium mg/kg
	91.27			1.24		8.55		0.004		0.418

2.2. Sample Preparation

Soil-cement samples admixed with recycled sand and with both recycled sand and nano-clay used in the direct shear test were placed in standard cylinders with a diameter of 61.8 mm and a height of 20 mm. Firstly, the order of mixing materials is sequential: soil, cement, recycled sand nano-clay and water were mixed. Then, the mixture was stirred for 10 min by a JJ-5 cement adhesive mixer, at a speed of 285 ± 10 r/min. Then, the mixture was stirred for 10 min. After the stirring was completed, the fixed mass was weighed, filled into the ring cutter, and pressed into shape by a hydraulic jack. Finally, the prepared samples were placed in a sealed box in a standard curing room for 7 days of curing.

2.3. Test Methods

Direct shear tests were carried out under the condition of controlled dry density (1.95 g/cm^3). The test was based on plain soil-cement, and divided into CSR admixed with recycled sand and CSRN admixed with recycled sand and nano-clay. The content of recycled sand was divided into four groups: 0%, 10%, 15% and 20%, and that of nano-clay was unified at 8%. The specific test scheme is shown in Table 5. The ratios of each material are specified in terms of soil mass percentage.

The SJ-1 electric strain direct shear apparatus, produced by Zhejiang Civil Engineering Instrument Manufacturing Co., Ltd., was used for the direct shear test of unsaturated soil, as shown in Figure 2. During the test, the upper and lower boxes were aligned and the fixing pin was inserted. The impervious plate was placed in the lower box, the flat opening of the ring knife was aligned with the shear box opening downward, the impervious plate was placed on the top surface of the sample, and then, the sample was pushed into the shear box slowly to remove the ring knife. The hand wheel was turned so that the ball at the front end of the upper box just made contact with the dynamometer. The dynamometer reading

was adjusted to zero. Considering that this study applied to the subgrade, four normal stresses were set, which were 100 KPa, 200 KPa, 300 kPa and 400 k, respectively. After the vertical stress was applied, the fixing pin was immediately removed. The stopwatch was started and cutting was performed at a rate of 0.8~1.2 mm/min to make the sample shear within 3~5 min. If the reading of the dynamometer is stable, or there is significant regression, the specimen has been sheared. Generally, the shear deformation should reach 4 mm. If the reading of the dynamometer continues to increase, the shear deformation should reach 6 mm. When the hand wheel rotates once, the reading of dynamometer and vertical displacement meter are measured and recorded at the same time until the shear loss.

Table 5. Test scheme.

Group	Soil-Cement (%)	Recycled Sand (%)	Nano-Clay (%)	Water (%)	Curing Period (d)
CSR-1	10	0	0	30	7
CSR-2	10	10	0	30	7
CSR-3	10	15	0	30	7
CSR-4	10	20	0	30	7
CSRN-1	10	0	8	30	7
CSRN-2	10	10	8	30	7
CSRN-3	10	15	8	30	7
CSRN-4	10	20	8	30	7



Figure 2. Electric strain-type direct shear apparatus.

3. Test Results

3.1. Shear Strength

The average value and standard deviation of shear strength of CSR and CSRN are shown in Tables 6 and 7, respectively.

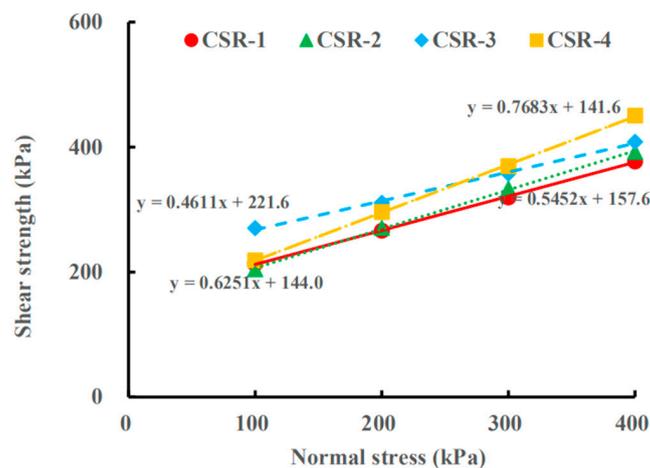
Table 6. Average value and standard deviation of shear strength of different content CSR.

Normal Stress	CSR-1 (kPa)	Standard Deviation	CSR-2 (kPa)	Standard Deviation	CSR-3 (kPa)	Standard Deviation	CSR-4 (kPa)	Standard Deviation
100	213.0	2.6	204.6	0.7	270.4	2.4	218.7	2.4
200	266.3	2.9	270.7	1.7	310.8	3.1	296.1	3.5
300	319.5	3.5	333.6	1.9	357.7	4.3	369.5	1.7
400	377.0	1.4	392.0	2.4	408.5	1.2	450.4	2.8

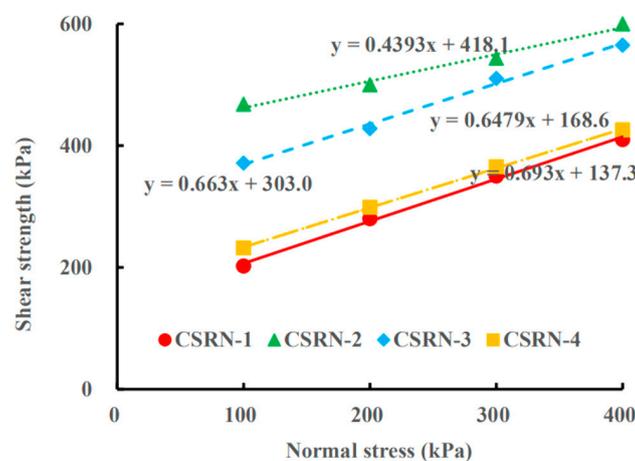
Table 7. Average value and standard deviation of shear strength of different content CSRN.

Normal Stress	CSRN-1 (kPa)	Standard Deviation	CSRN-2 (kPa)	Standard Deviation	CSRN-3 (kPa)	Standard Deviation	CSRN-4 (kPa)	Standard Deviation
100	202.3	2.6	468.1	1.5	371.5	1.5	232.0	1.4
200	280.0	1.7	500.0	1.4	428.0	1.9	299.0	3.4
300	350.0	2.8	543.6	1.4	510.4	2.0	365.4	2.0
400	410.0	2.2	600.0	1.2	565.0	3.4	425.8	2.6

Figure 3 shows the relationship between normal stress and shear strength of CSR and CSRN. It can be seen from Figure 3 that shear strength increases almost linearly with positive stress. Among the four CSR groups, CSR-1 has the lowest shear strength at all four normal stresses. However, among the four CSRN groups of soil-cement, CSRN-1 showed the smallest shear strength at all four normal stresses, CSRN-2 showed the largest shear strength at all four normal stresses, and CSRN-4 improved the least. The shear strength of CSRN-1 and CSRN-4 ranges from 202.3 kPa to 600 kPa, and the overall shear strength of CSRN-2 and CSRN-3 is higher than that of CSRN-1 and CSRN-4, which ranges from 371.5 kPa to 600.0 kPa. The obvious change in shear strength may be due to the nano-clay interfering with the internal action mechanism of cement-soil and breaking the balance of the strength increase system of cement-soil.



(a)



(b)

Figure 3. Relationship between shear strength and normal stress (a) CSR, (b) CSRN.

In order to judge the changes in shear strength of the four groups of CSR and CSRN samples more intuitively, the normalized shear strength is used to compare the changes in the shear strength of different groups [12]. The specific calculation formula is shown in Equation (1):

$$N = \frac{S}{R} \quad (1)$$

where N represents the standardized shear strength; S represents the shear strength of different CSR and CSRN with different recycled sand content; R represents the shear strength of CSR-1 or CSRN-1 corresponding to S .

Figure 4 shows the normalized shear strength. It can be seen from Figure 4a that 15% is the optimal recycled sand content, with which the maximum stress increase is obtained. When the recycled sand content is 15%, the normalized shear strength is from 1.03 ($\sigma = 400$ kPa) to 1.27 ($\sigma = 100$ kPa). In addition, for high normal stress ($\sigma = 300$ kPa or 400 kPa), the overall shear strength of soil-cement increases with the addition of recycled sand. However, for low normal stress ($\sigma = 100$ kPa or 200 kPa), recycled sand will sometimes weaken the shear strength. When $\sigma = 100$ kPa, the standard shear strength is only 0.96 when 10% recycled sand content is added, and the strength drops by 4%.

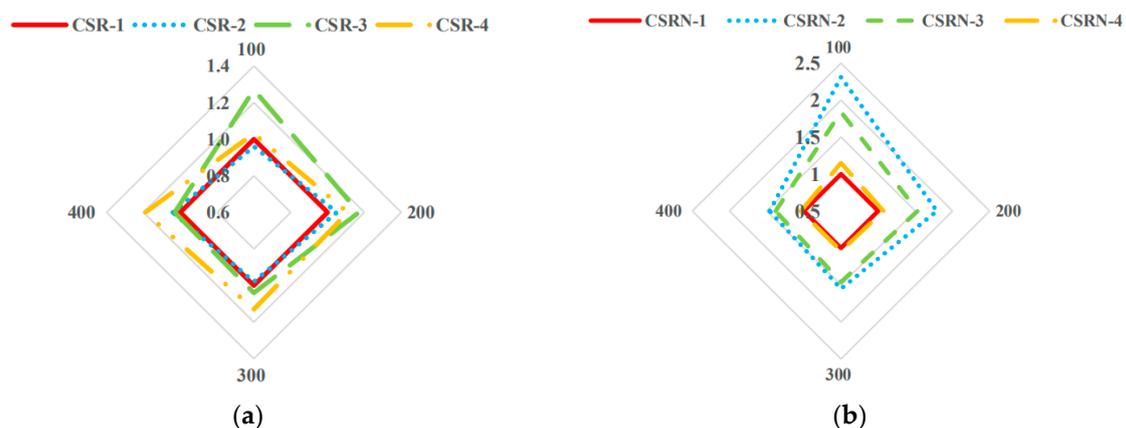


Figure 4. Normalized shear strength (a) CSR, (b) CSRN.

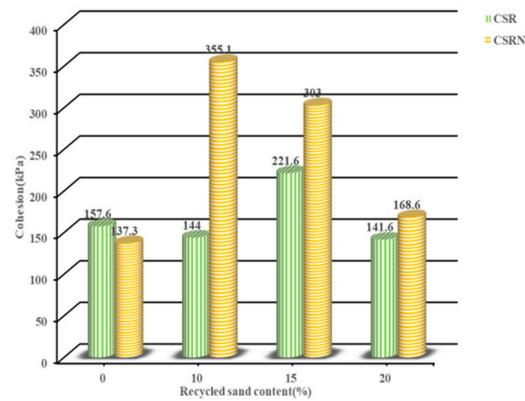
CSRN was obtained by adding 8% nano-clay to CSR, and the modification effect of nano-clay on the shear strength of soil-cement was further studied. At the same time, the normalized shear strength index is quoted and obtained after calculation. Figure 4b shows the normalized shear strength of CSRN. It can be clearly seen from Figure 4b that under the additional action of same nano-clay content, the optimal recycled sand content is 10%, which is 5% less than that of CSR, but the maximum stress increase is obtained. When the recycled sand content is 10%, the normalized shear strength is from 1.46 ($\sigma = 400$ kPa) to 2.31 ($\sigma = 100$ kPa). In addition, with the increase in recycled sand content, four normal stresses all show a consistent trend of increasing and then decreasing, all of which are at the maximum when the recycled sand content is 10%, and the most obvious under low normal stress. When $\sigma = 100$ kPa, the normalized shear strength of CSRN-2 is 2.31, and the strength increases by 31%.

3.2. Internal Friction Angle and Cohesion

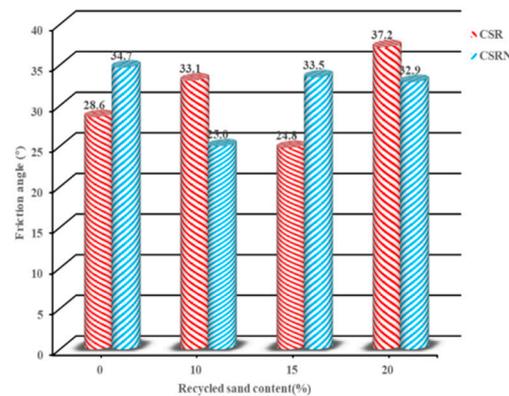
According to the Mohr–Coulomb principle in Equation (1), the cohesion c and internal friction angle φ of CSR and CSRN were calculated and plotted in Figure 5.

$$\tau = c + \sigma \tan \varphi \quad (2)$$

where τ represents the shear strength, and the unit is kPa; σ represents the normal stress, and the unit is kPa; c represents the cohesion, and the unit is kPa.



(a)



(b)

Figure 5. Cohesion (a) and internal friction angle (b) of CSR and CSRN.

The shear strength of soil-cement can be explained by the change in shear strength parameters (c and φ) along with different recycled sand content, as shown in Figure 5. It can be seen from Figure 5a that when the recycled sand content is 15%, the cohesion of CSRN-1 increases compared with that of CSR-1. In terms of other recycled sand content (10% and 20%), the addition of recycled sand leads to a decrease in the cohesion of soil-cement. This indicates that the addition of recycled sand may have an adverse effect on the cohesion of soil-cement, but the optimal recycled sand content of 15% can significantly improve the cohesion of soil-cement. However, the internal friction angle shows the opposite trend. As shown in Figure 5b, when the recycled sand content is moderate (15%), the internal friction angle of CSRN-1 tends to decrease compared with that of CSR-1. When the recycled sand content is 20%, the maximum internal friction angle is obtained.

At the same time, the shear strength variation of CSRN with the change in recycled sand content was analyzed from the shear strength parameters (c and φ). It can be seen from Figure 5a that when the recycled sand content is 10%, the cohesion of CSR-1 increases the most compared with that of CSRN-1, increasing by 280.7 kPa, while the cohesion of CSRN-2 and CSRN-3 also increases, but with a small increase, and this increasing trend decreases with the increase in recycled sand content. This indicates that with the assistance of nano-clay, the adverse effect of the addition of recycled sand in CSR on the cohesion of soil-cement disappears, and the degree of increase in the cohesion of soil-cement under the condition of optimal recycled sand content can be greatly improved. In terms of internal friction angle, the phenomenon that the internal friction angle of CSR presents a trend contrary to the cohesion also appears in CSRN. As shown in Figure 5b, CSRN-2 with the

largest cohesion shows the smallest internal friction angle, which is 25.0° . However, by adding nano-clay to CSR, the internal friction angles of CSRN-2, CSRN-3 and CSRN-4 all decrease. This indicates that nano-clay can further reduce the large internal friction angle caused by recycled sand.

4. Microstructure Characteristics

In order to further understand the geotechnical properties of CSR and CSRN, and to provide supporting evidence to explain the hypothesis that recycled sand and nano-clay can improve the engineering properties of soil-cement, representative samples were taken for SEM microscopic tests, and the SEM images were quantitatively analyzed by IPP software.

4.1. SEM

Figure 6a,c,e,g show the typical SEM images of CSR samples. Among them, Figure 6a shows a sample without recycled sand content, from which it can be observed that there are many large particles with large pores, and the connection between the large particles is poor. Overall, the framework of the structure is loose. When the recycled sand content is 10%, as shown in Figure 6c, the connection is obviously better, which is reflected in the reduction in particle volume and the pores between particles. This is because when recycled sand is added, the hardness of the recycled sand replaced by an equal volume of soil particles is greater, and its squeezing effect on soil particles makes the soil particles relatively denser. The samples in the CSR-3 group with the best content are shown in Figure 6e. Its overall performance is denser and the pores are smaller. This is because more recycled sand is mixed to make the unity better. Figure 6g shows that when the recycled sand content is 20%, the sample is slightly looser than CSRN-3, which is consistent with the shear strength results in the direct shear test.

Figure 6b,d,f,h show the typical SEM images of CSRN samples. Compared with that of the CSR samples in Figure 6a,c,e,g, the overall density is slightly higher with many agglomerates, which is due to the excellent properties of nano-clay. On the one hand, the "filling effect" of nano-clay can fill nano-sized pores, thereby improving the density of the soil-cement as a whole. On the other hand, when a small amount of nanoparticles are uniformly dispersed in soil-cement, the hydration products of the cement are deposited on the nanoparticles due to the huge surface energy during the hydration process, and grow to form aggregates with nanoparticles as the core [24]. Taking into account the uniform dispersion of nanoparticles, a good microstructure with uniform distribution of agglomerates can be formed. Among the SEM images of four samples groups, Figure 6d shows the largest degree of density, that is, the SEM microscopic image of CSRN-2 with 10% recycled sand content, which is also consistent with the direct shear test data.

It can also be seen from Figure 6 that the microscopic images of CSR groups are larger than that of CSRN groups, which can also explain why CSR has a larger internal friction angle and smaller cohesion. This is because when the particle size inside the soil-cement is large, the contact area of the particle is small, the surface is rough, and the cohesion between particles is also small, the relative slippage between particles inside the soil-cement is also large, resulting in a greater internal friction angle. When the size of the particle is small, the contact area of the particle is larger, and the cohesion generated by bonding and structure of the internal particles of soil-cement is also larger.

4.2. Void Ratio Analysis

Since there is an obvious jump in the gray value between particles and pores in the SEM image, the particles or pores can be segmented from the background accordingly for further quantitative analysis. Image-Pro Plus (IPP) is used to process the SEM images of the CSR samples. Firstly, threshold segmentation is carried out to adjust the overall threshold of the image. Particles are segmented from the background by jumping the gray value on the boundary, and then, the gray image is converted into a black-and-white binary

image—that is, the soil-cement particles in the image are recorded as white, and the pores are recorded as black, as shown in Figure 7. In order to quantitatively reflect the pores of the soil-cement, the void ratio P is introduced:

$$P = \frac{A_b}{A_t} \times 100\% \quad (3)$$

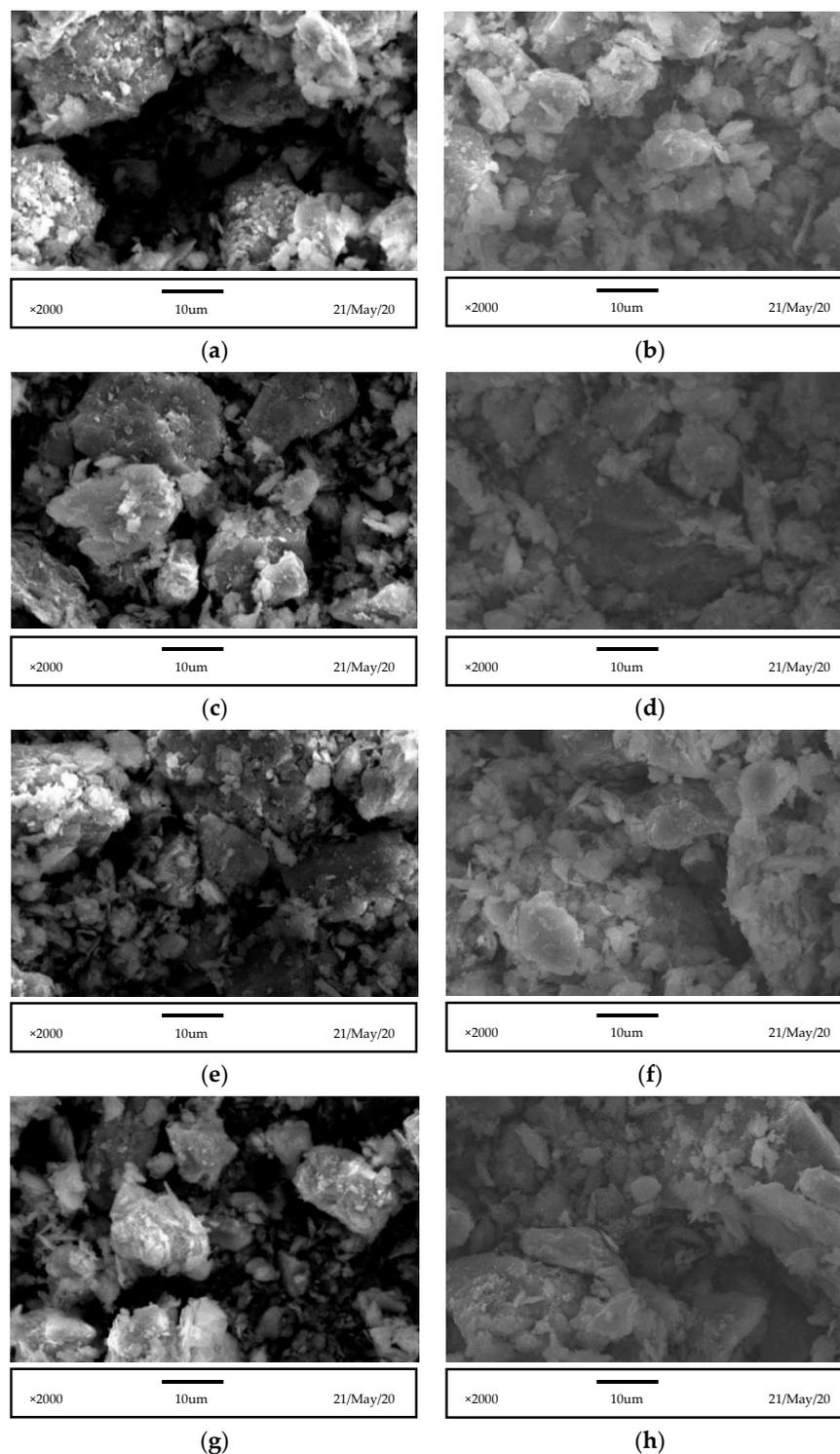


Figure 6. SEM images: (a) CSR-1; (b) CSRN-1; (c) CSR-2; (d) CSRN-2; (e) CSR-3; (f) CSRN-3; (g) CSR-4; (h) CSRN-4.

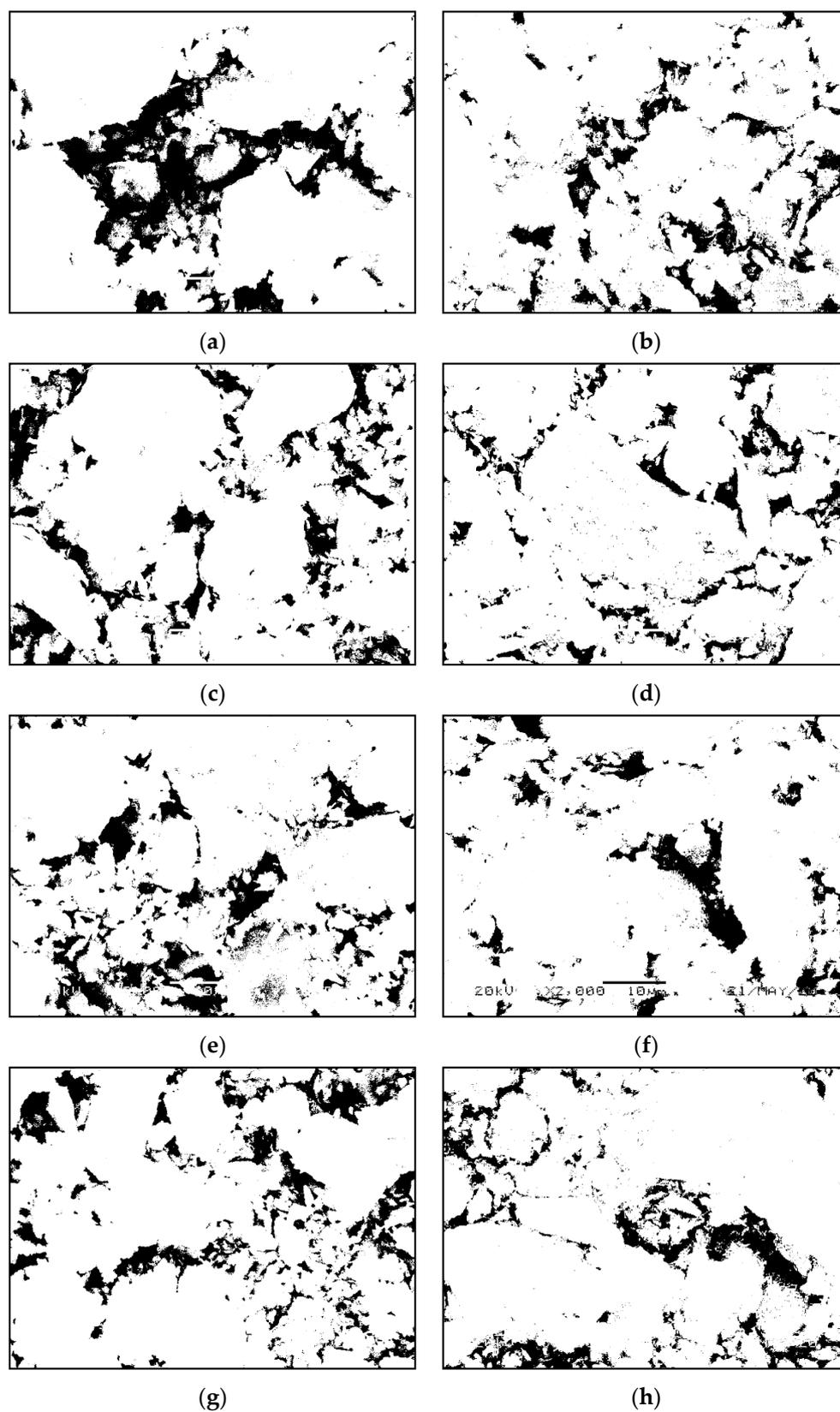


Figure 7. SEM binary images: (a) CSR-1; (b) CSRN-1; (c) CSR-2; (d) CSRN-2; (e) CSR-3; (f) CSRN-3; (g) CSR-4; (h) CSRN-4.

That is, the area of the black pores (A_b) is divided by the total area (A_t) of the SEM image. P can be automatically calculated by the Measure command in the IPP software, as

shown in Table 8. The image analysis was repeated three times at different locations for each mix.

Table 8. The void ratio of CSR and CSRN (%).

Content of Recycled Sand (%)	CSR			CSRN		
	CSR	Average	Standard Deviation	CSR	Average	Standard Deviation
0	35.6	33.4	36	31.8	30.4	27.8
10	32.2	34.3	32.5	28.6	27.5	30.9
15	30.9	29.1	33	29	29.5	31.5
20	31.5	34.3	33.2	31.3	32.1	29.6

Figure 8 shows comparison images of the average void ratio of CSR and CSRN. It can clearly be seen from the figure that the void ratio of the CSRN groups is smaller than that of the CSR groups, and both present a trend of first decreasing and then increasing. CSR and CSRN reach their minimum values of void ratio at 14.0% and 10.0% when the recycled sand content is 15% and 10%, respectively, which is consistent with the intuitive perception of SEM microscopic images and direct shear test data. Therefore, the internal density of the soil-cement is positively related to the shear strength. The greater the density, the greater the shear strength.

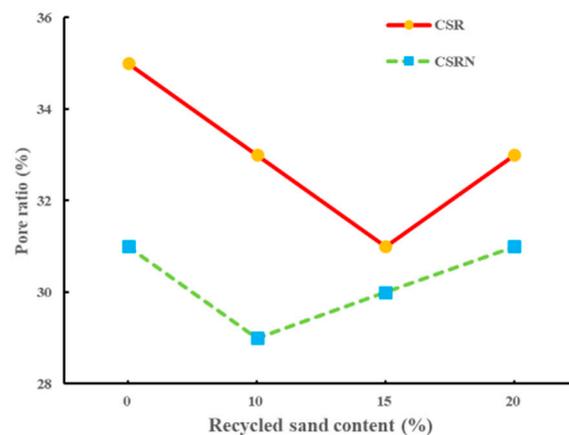


Figure 8. Comparison of average void ratio.

5. Mechanism Analysis

Soil shear strength is determined by the connection strength of soil particles in the soil mass. After admixing with a certain amount of cement in soft soil, C-S-H gelation can be produced by cement under the action of a hydration reaction. The existence of this gelation improves the connection strength between soil particles and is also the main source of strength in soil-cement.

5.1. CSR

The shear strength of the soil-cement is improved by admixing with a certain amount of recycled sand. This is because the incorporation of recycled sand makes soil-cement contain the aggregates existing in concrete. Soil-cement can be regarded as “concrete-like”—that is, its strength is close to the strength of concrete. The increase in the strength of this “concrete-like” product is due to the replacement of some soil particles with recycled sand. Recycled sand replaces part of the soil, which increases the shear strength of the damaged surface and restricts further development of the damaged surface of soil-cement. At the same time, under the joint action of cement, soil and recycled sand, the C-S-H gelation produced by the cement hydration reaction greatly enhances the connectivity between soil

particles and recycled sand particles, thereby improving the overall density of soil-cement, which is further manifested as an increase in the shear strength of soil-cement.

The optimal content of recycled sand in CSR is 15%, which is mainly because when the recycled sand content is too high, the cohesion between soil particles decreases and the friction force between particles decreases during the movement, which leads to the weakened shear resistance of soil-cement. At the same time, because the content of cement is fixed, the C-S-H supply keeps constant. When the recycled sand content increases to exceed the saturation value of C-S-H gelation provided by the existing cement, the C-S-H gelation used to connect the soil particles and recycled sand particles is in short supply, and the bonding force between soil and recycled sand particles decreases, resulting in a decrease in shear strength.

5.2. CSRN

CSRN was formed by admixing 8% nano-clay with CSR, and the shear strength was further improved. This can be attributed to: (1) the filling effect of nano-clay particles, because their nanoparticles fill the existing pores in soil-cement to make it fully compacted; (2) the high pozzolanic activity of nano-clay particles reacts with CH to generate additional C-S-H gelation [26]. Therefore, nano-clay optimizes the mechanical properties of soil-cement from both physical and chemical aspects, and further strengthens the shear strength of the above-mentioned “concrete-like”, which is represented by the overall improvement in the shear strength of CSRN.

The addition of nano-clay changed the optimal recycled sand content in soil-cement from 15% to 10%. This is because in this test, the content of cement is fixed, and the addition of nano-clay will react with part of the cement. Although it can generate additional C-S-H gelation, this is not enough; the C-S-H gelation used to connect soil particles and recycled sand particles decreases, causing the above-mentioned insufficient supply of C-S-H gelation in advance. Therefore, in the direct shear test of CSRN, the optimal recycled sand content of 15% in CSR cannot be maintained.

5.3. Particle Size

The size of the particles in the different materials is an important factor affecting the internal structure of the soil-cement. In order to reveal the action mechanism of the size of the recycled sand and nano-clay particles on the internal structure of the soil-cement, a schematic diagram is drawn at the mm scale, as shown in Figure 9. The soil particles are connected by van der Waals force, Coulomb force, cementation and capillary force, resulting in different properties of the soil in the direction perpendicular to the directional arrangement and parallel to the directional arrangement—that is, it has anisotropy. The existence of this anisotropy and the irregularity of particle size often result in a large number of pores between soil particles, as well as soil-cement, as shown in Figure 9a.

When an appropriate amount of recycled sand and nano-clay are added into the soil-cement in a certain proportion, it can be clearly seen that the pores of CSR and CSRN gradually decrease compared with plain soil-cement; the internal structure diagrams of CSR and CSRN are shown in Figure 9b,c. This is because in CSR, recycled sand has a more regular shape after processing, and its hardness is greater than that of soil with no viscosity. Therefore, it can be more rationally distributed among soil particles, and to a certain extent, it can fill the pores between soil particles. On the other hand, in CSRN, the size of nano-clay ranges from 1 nm to 100 nm, which is much smaller than that of cement and recycled sand. Therefore, nano-clay can not only fill the pores between soil particles, but also fill the pores between recycled sand particles, so as to improve the density of soil-cement as a whole.

In addition, in the case of a certain pattern volume, the internal structure arrangement of different recycled sand content will be different, and there will be an optimal arrangement. In the CSR soil-cement only mixed with recycled sand—the optimal arrangement of internal structure of CSR-3 with 15% recycled sand content—the recycled sand particles with internal structure are evenly distributed in the soil-cement. The recycled sand particles

have less contact with each other, and the soil brings more cohesion, so it shows lower internal friction angle. After adding 8% nano-clay into CSR to obtain CSRN, the smaller nano-clay is filled between soil-cement and recycled sand particles in limited space, and the internal structure of soil-cement is reorganized. The internal structure of CSRN-2 with 10% recycled sand has an optimal arrangement, and also shows a lower internal friction angle. This explains the variation of internal friction angle of CSR and CSRN in Figure 5b well.

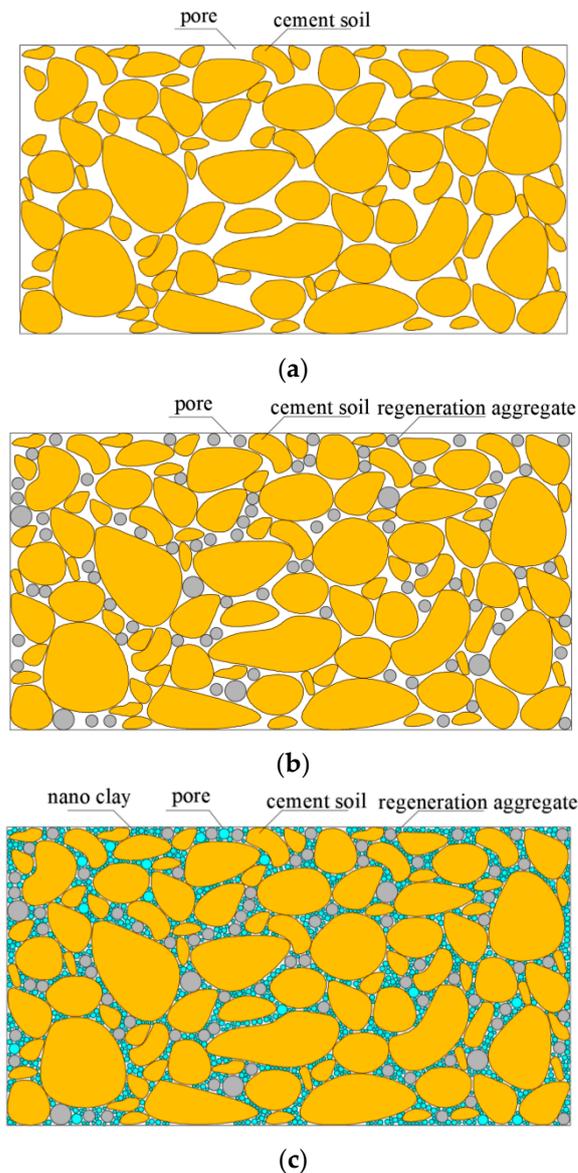


Figure 9. Internal structures of (a) soil-cement, (b) CSR, (c) CSRN.

6. Conclusions and Discussion

6.1. Conclusions

In order to study the influence of recycled sand and nano-clay on the shear strength of soil-cement in a coastal area, direct shear tests were carried out using recycled sand and nano-clay with different contents and proportions, and the following conclusions were obtained through SEM tests.

1. For CSR, the addition of recycled sand can increase the shear strength of soil-cement. CSR-3 has the best improvement effect on the shear strength with a recycled sand content of 15%. This is because after the recycled sand is added to soil-cement in the form of aggregate, soil-cement transforms into a “concrete-like” product. However,

the addition of too much non-viscous recycled sand will reduce the cohesion between the internal particles of soil-cement, which will lead to a decrease in the increase in shear strength.

2. For CSRN, after adding 8% nano-clay to CSR, the overall shear strength increases. CSRN-2 has the best improvement effect on the shear strength with a recycled sand content of 10%, and its shear strength was greater than that of CSR-3. This is because the “filling effect” of nano-clay can increase the shear strength of soil-cement. On the other hand, nano-clay can react with cement to form more C-S-H gelation, thereby improving the cohesion of soil-cement as a whole and indirectly enhancing the shear strength of soil-cement.
3. For the SEM test, through the direct observation of SEM images and further processing by IPP software, SEM images on the microscopic scale are quantitatively analyzed. It is concluded that CSR-3 has the largest density and the smallest porosity among the four groups of CSR samples; CSRN-2 has the largest density and smallest porosity among the four groups of CSRN samples, which is consistent with the results of direct shear test.
4. For the analysis of the internal structure of soil-cement in mm size, there are large pores between the original irregular soil particles, which are filled to a certain extent after adding more regular recycled sand and smaller nano-clay. Therefore, the addition of recycled sand and nano-clay can make the internal structure distribution of soil-cement more reasonable.

6.2. Discussion

This study still has the following shortcomings, which need to be studied further.

- (1) Discussion on long curing period. This study only studies the shear strength of CSR and CSRN at the early stage; actual engineering requires the shear strength test results at a curing period of 28 d or even 90 d.
- (2) Diversified experimental exploration. This test only carried out direct shear tests, but the exploration of the mechanical properties of a material should be diversified. In future studies, more comprehensive mechanics research shall be carried out for unconfined, conventional triaxial, true triaxial, resonance column and dynamic triaxial tests, so as to fully reveal the mechanism of the material and enhance the scope of engineering applications.
- (3) Research on reclaimed sand, a sustainable material combined with a new material—nano-clay—to modify soil-cement in coastal areas, is still in the indoor test stage; it needs to be further tested in actual engineering construction in the future.

Author Contributions: All authors contributed substantially to this study. Individual contributions are: conceptualization, B.Q.; data curation, W.Y.; Formal analysis, B.L.; writing—review and editing, H.K.; investigation, L.S.; methodology, N.L.; project administration, W.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (Grant numbers [41772311]), and the Research Fund of Zhejiang Provincial Department of Housing and Urban-Rural Development (2017K179, 2019K171).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Cheng, Q.; Xiao, H.; Liu, Y.; Wang, W.; Jia, L. Primary yielding locus of cement-stabilized marine clay and its applications. *Mar. Georesour. Geotechnol.* **2018**, *37*, 488–505. [[CrossRef](#)]
2. Li, N.; Zhu, Q.; Wang, W.; Song, F.; An, D.; Yan, H. Compression Characteristics and Microscopic Mechanism of Coastal Soil Modified with Cement and Fly Ash. *Materials* **2019**, *12*, 3182. [[CrossRef](#)]
3. Zhou, J.; Yu, J.; Gong, X.; El Naggari, M.H.; Zhang, R. The effect of cemented soil strength on the frictional capacity of precast concrete pile–cemented soil interface. *Acta. Geotech.* **2020**, *15*, 3271–3282. [[CrossRef](#)]
4. Lang, L.; Liu, N.; Chen, B. Strength development of solidified dredged sludge containing humic acid with cement, lime and nano-SiO₂. *Constr. Build. Mater.* **2020**, *230*, 116971. [[CrossRef](#)]
5. Li, N.; Lv, S.; Wang, W.; Guo, J.; Jiang, P.; Liu, Y. Experimental investigations on the mechanical behavior of iron tailings powder with compound admixture of cement and nano-clay. *Constr. Build. Mater.* **2020**, *254*, 119259. [[CrossRef](#)]
6. Thomas, C.; de Brito, J.; Cimentada, A.; Sainz-Aja, J.A. Macro- and micro- properties of multi-recycled aggregate concrete. *J. Clean. Prod.* **2020**, *245*, 118843. [[CrossRef](#)]
7. Tam, V.W.Y.; Soomro, M.; Evangelista, A.C.J. A review of recycled aggregate in concrete applications (2000–2017). *Constr. Build. Mater.* **2018**, *172*, 272–292. [[CrossRef](#)]
8. Tong, H.; Ouyang, S.X.; Bi, Y.P.; Umezawa, N.; Oshikiri, M.; Ye, J.H. Nano-photocatalytic Materials: Possibilities and Challenges. *Comput. Adv. Mater.* **2012**, *24*, 229–251. [[CrossRef](#)]
9. Chen, J.; Qiu, H.; Zhao, S. Fabrication of chemiluminescence resonance energy transfer platform based on nanomaterial and its application in optical sensing, biological imaging and photodynamic therapy. *TrAC Trends Anal. Chem.* **2020**, *122*, 115747. [[CrossRef](#)]
10. Yao, K.; Wang, W.; Li, N.; Zhang, C.; Wang, L. Investigation on strength and microstructure characteristics of nano-MgO admixed with cemented soft soil. *Constr. Build. Mater.* **2019**, *206*, 160–168. [[CrossRef](#)]
11. Naseri, F.; Irani, M.; Dehkhodarajabi, M. Effect of graphene oxide nanosheets on the geotechnical properties of cemented silty soil. *Arch. Civ. Mech. Eng.* **2016**, *16*, 695–701. [[CrossRef](#)]
12. Yao, K.; An, D.; Wang, W.; Li, N.; Zhang, C.; Zhou, A. Effect of nano-MgO on mechanical performance of cement stabilized silty clay. *Mar. Georesour. Geotechnol.* **2020**, *38*, 250–255. [[CrossRef](#)]
13. Sobolev, K.; Flores, I.; Torres-Martinez, L.; Valdez, P.; Zarazua, E.; Cuellar, E. Engineering of SiO₂ Nanoparticles for Optimal Performance in Nano Cement-Based Materials. In *Nanotechnology in Construction 3*; Springer: Berlin/Heidelberg, Germany, 2009; pp. 139–148.
14. Nima, F.; Ali, A.A.A.; Demirboga, R. Development of Nanotechnology in High Performance Concrete. *Adv. Mater. Res.* **2011**, *364*, 115–118. [[CrossRef](#)]
15. Ltifi, Guefrech, A.; Mounanga, P.; Khelidj, A. Experimental study of the effect of addition of nano-silica on the behaviour of cement mortars Mounir. *Procedia Eng.* **2011**, *10*, 900–905. [[CrossRef](#)]
16. Hou, P.; Wang, K.; Qian, J.; Kawashima, S.; Kong, D.; Shah, S.P. Effects of colloidal nanoSiO₂ on fly ash hydration. *Cem. Concr. Compos.* **2012**, *34*, 1095–1103. [[CrossRef](#)]
17. Lin, K.L.; Chang, W.C.; Lin, D.F.; Luo, H.L.; Tsai, M.C. Effects of nano-SiO₂ and different ash particle sizes on sludge ash-cement mortar. *J. Environ. Manag.* **2008**, *88*, 708–714. [[CrossRef](#)] [[PubMed](#)]
18. Stefanidou, M.; Papayianni, I. Influence of nano-SiO₂ on the Portland cement pastes. *Compos. Part B. Eng.* **2012**, *43*, 2706–2710. [[CrossRef](#)]
19. Gaitero, J.J.; Campillo, I.; Guerrero, A. Reduction of the calcium leaching rate of cement paste by addition of silica nanoparticles. *Cem. Concr. Res.* **2008**, *38*, 1112–1118. [[CrossRef](#)]
20. Tabarsa, A.; Latifi, N.; Meehan, C.L.; Manahiloh, K.N. Laboratory investigation and field evaluation of loess improvement using nanoclay—A sustainable material for construction. *Constr. Build. Mater.* **2018**, *158*, 454–463. [[CrossRef](#)]
21. Zoriyeh, H.; Erdem, S.; Gürbüz, E.; Bozbey, İ. Nano-clay modified high plasticity soil as a building material: Micro-structure linked engineering properties and 3D digital crack analysis. *J. Asian Archit. Build.* **2020**, *27*, 101005. [[CrossRef](#)]
22. Wang, W.; Li, J.; Hu, J. Unconfined mechanical properties of nanoclay cement compound modified calcareous sand of the South China Sea. *Adv. Civ. Eng.* **2020**, 6623710. [[CrossRef](#)]
23. Wang, W.; Li, Y.; Yao, K.; Li, N.; Zhou, A.; Zhang, C. Strength properties of nano-MgO and cement stabilized coastal silty clay subjected to sulfuric acid attack. *Mar. Georesour. Geotechnol.* **2020**, *38*, 1177–1186. [[CrossRef](#)]
24. Ghasabkolaei, N.; Choobbasti, A.J.; Roshan, N.; Ghasemi, S.E. Geotechnical properties of the soils modified with nanomaterials: A comprehensive review. *Arch. Civ. Mech. Eng.* **2017**, *17*, 639–650. [[CrossRef](#)]
25. Wang, W.; Zhang, C.; Guo, J.; Li, N.; Li, Y.; Zhou, H.; Liu, Y. Investigation on the Triaxial Mechanical Characteristics of Cement-Treated Subgrade Soil Admixed with Polypropylene Fiber. *Appl. Sci.* **2019**, *9*, 4557. [[CrossRef](#)]
26. Xiao, H.; Zhang, F.; Liu, R.; Zhang, R.; Liu, Z.; Liu, H. Effects of pozzolanic and non-pozzolanic nanomaterials on cement-based materials. *Constr. Build. Mater.* **2019**, *213*, 1–9. [[CrossRef](#)]