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Research Article

Effects of Soil Properties on the Performance of TRD Cut-Off Wall

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The trench cutting remixing deep wall (TRD) method is a new cement soil cut-off wall construction technique, which has been widely used in cofferdam, embankment dam, and underground waterproof curtain structures. The chain cutter of TRD moves horizontally to cut and stir different soil layers by up and down to form a cement-mixed soil diaphragm wall with continuous and uniform thickness, the mechanics and permeability of which are obviously different from those of cement soil with a horizontally mixed single soil layer in traditional deep mixing pile (DMP). In this paper, five sets of onsite walling tests with different cement ratios were carried out to analyse the unconfined compression and permeability of undisturbed cement-mixed soil in TRD. The difference of both unconfined compressive and permeability coefficients in between TRD and DMP was analysed to discuss the stirring performance of TRD. Then, the microscopic mechanism of soil properties affecting the performance of cement-mixed soil has been studied by scanning electron microscopy (SEM) in the unconfined compression strength test and permeability coefficient test of cement soil with different mixed soil properties. The test results show that the unconfined compressive strength of cement-mixed soil is closely correlated to its gradation. As the mixed soil gradation curve approaches to the Fuller curve, the unconfined compressive strength would gradually increase. In mesoscopic, cement fine sand has a large pore structure, and the average pore area is 2.46 times as cement clay. The permeability coefficient of cement-mixed soil is controlled by the proportion of fine sand content with high permeability.

1. Introduction

The cement cut-off wall is a waterproof curtain structure for cofferdam, embankment dam, and underground engineering. In order to be applied in different geological conditions, several new construction techniques on deep cement soil mixing cut-off wall have emerged with the progress of construction machine in recent years, such as SMW [1], TRD [2], and CSM [3, 4]. The trench cutting remixing deep wall (TRD) uses a chain saw box to horizontally push through the stratum and to vertically cut the soil layers in the meantime, and then the cement slurry is injected to the mix and the cement-mixed soil is stired to form a continuous underground wall with uniform thickness. Compared with traditional deep mixing pile (DMP), the significant difference between deep mixing pile to TRD is soil properties in the mixed cement soil. DMP is to horizontally stir and mix the soil and cement in the single soil layer, but TRD is to vertically stir and mix the soil and cement in all soil layers. The cement soil of DMP is the mixing soil between cement and soil in a single stratum, and the cement soil of TRD is the mixing soil between cement and mixed soil in multiple stratums.

Many scholars have carried out systematic research on the cement-soil mix ratio, solidification mechanism, microstructure, mechanics, seepage, and cement soil improvement in the field of cement soil research. In terms of the influence of soil properties, Ismail et al. [5] have studied the shear properties of different types of cement soil by triaxial tests. Chian [6] discussed the influence of mix proportions, curing time, and sand impurities on the strength development of cement-treated clayey soils. Yao et al. [7] proposed a framework describing the effect of mix ratio, mean effective stress, and overconsolidation on the modulus degradation behaviour of cement-treated soil through the unconfined compressive strength. Miura et al. [8, 9] found that the ratio of water and cement played a dominating role in the strength characteristics and deformation characteristics of the solidified soil and is used to characterize the strength of solidified soil. Liu and Starcher [10] discovered that the unconfined compressive strength of soft soil cement increases as the curing age and stress of solidification, and the stiffness of soft soil cement significantly improves as well under the solidification stress. Consoli et al. [11] established a functional relationship among the unconfined compressive strength, the splitting strength, cement content, and porosity of fibre-reinforced fine-grained cement soil. Miller and Azad [12] found that the unconfined compressive strength of cemented soil was inversely proportional to the plasticity index of the reinforced clay and was directly proportional to the clay content. Tomac et al. [13] found that the macroscopic strength of marine sedimentary soil cement was related to the microstructure characteristics of cement soil. Xiao et al. [14, 15] researched the unconfined compressive strength and yield stress of marine sedimentary soil cement and found that the variation of the mixed composition exerts an important impact on the bearing capacity as well as waterproof performance of the cement soil cut-off wall.

The solidification mechanism of cement soil is much more complicated under the influence of different soil properties. Researches on the microscopic mechanism of geomaterials are continuously developing along with the update of detection techniques, such as scanning electron microscopy (SEM), mercury intrusion, X-ray diffraction, pH analysis, and displacement tracing with microscope. [16–18]. Researches on microscopic mechanism of cement soil have been mainly carried out from two aspects including microstructure and material composition. In term of microstructure, Wang et al. [19] quantitatively analysed the microstructure of cement soft soil by SEM and image processing technique. Yin et al. [20] analysed the microstructure characteristics of cement soft soil with the help of microstructure observation methods such as pore size analysis, X-ray diffraction, and SEM and demonstrated the reinforcement mechanism of cement soil. Han et al. [21] analysed the effect of sodium sulphate on the microspore structure of cement soil by SEM. Yu et al. [22] also used SEM to study the effect of water-reducing agent on the microstructure of cement and lime-solidified soft soil. In terms of material composition, Huang and Zhou [23] analysed the chemical composition of pore water and cement hydrate in cement soil and discovered that the cement hydrate generation is influenced by surrounding soil medium on the absorption of calcium ions. Li et al. [24] proposed that clay minerals in soft soil adsorbing calcium ions also affected the formation of fibrous hydrated calcium silicate, which would directly affect the result of reinforcement. Ding and Zhang [25] tested the sedimentary silt cement soil by the X-ray diffraction and explained the internal mechanism of cement soil swelling performance from the view of mineral formation. The cement soil can be altered by the composition of soil material by a series of physicochemical reactions between the curing agents and the material components so as to achieve the required curing effect.

In summary, researches on cement soil have been mainly focused on investigating a single type of cement soil and have been hardly focused on investigating cement-mixed soil. Moreover, existing researches indicated that the microstructure and material composition play two important roles in influencing the material mechanics of cement soil. This paper firstly carried out five sets of onsite walling tests with different cement ratios to acquire the unconfined compression and permeability of undisturbed cement-mixed soil in TRD. The difference of both unconfined compressive and permeability coefficients between TRD and DMP was discussed to reveal the stirring mechanism of TRD and so did the stirring performance of TRD. Secondly, the relationship among the microstructure, material composition, and mechanics of cement-mixed soil is discussed based on scanning electron microscopy (SEM) technique to reveal the influence of soil properties on the engineering performance of cement-mixed soil.

2. Undisturbed Cement-Mixed Soil Test

2.1. Overview of Project. The construction site is located in Qingshan District of Wuhan City, adjacent to the right bank of the Yangtze River, the stratum of which has a thick and strong permeable layer. The distribution of the soil layers and their physical and mechanical properties are shown in Table 1. The foundation pit is 25 m away from the right bank of the Yangtze River, covering an area of about 12,350 m^2, the perimeter of which is about 420 m and about 15 m in depth. The waterproof curtain was a drop-bottom cement soil wall with equal thickness built by TRD.

2.2. Onsite Walling Test. Five onsite walling tests were carried out, each wall of which is 2800 mm in length and 800 mm in thickness, and the corresponding depth, cement content, and water cement ratio are shown in Table 2. In addition, 450 kg P.O. 42.5 grade ordinary Portland cement and about 100 kg/m^3 sodium bentonite were mixed per cubic of cement-mixed soil.

The deviation of wall verticality, wall position, wall depth, and wall thickness are, respectively, limited in less than 1/300, kept within +20 mm~−50 mm, limited in less than 50 mm, and controlled within 0~−20 mm. The processing of onsite wall construction has three steps including beforehand excavation, withdrawal excavation, and cement soil mixing according to the operating procedure of TRD.

2.3. Core-Drilling Sampling. After 20 days of curing time, the core specimens of undisturbed cement soil were drilled at different depths, the corresponding positions of which are shown in Table 3 and the pictures of which are shown in

Table 1: Physical and mechanical indices of soil layers.

Soil layer	Elevation of layer bottom (m)	Unit weight γ (kN·m^{-3})	Consolidation quick-direct indices		SPT blow count	Permeability coefficient (cm·s^{-1})
			Cohesion (kPa)	Internal friction angle, φ (°)		
1. Filing soil	4	—	—	—	3.3	1.50×10^{-3}
2. Silty clay	7.5	18.0	14.5	9.0	4.8	3.92×10^{-5}
3_1. Silt mixed with silty sand	10.9	18.5	18.0	14.0	10.1	1.24×10^{-4}
3_2. Silty sand	20	18.6	0.0	25.0	11.8	2.67×10^{-3}
4_1. Fine sand I	30	18.6	0.0	32.3	15.4	5.28×10^{-3}
4_2. Fine sand II	45	18.6	0.0	37.8	27.1	5.56×10^{-3}
4_3. Coarse sand with gravel	46.8	19.6	0.0	40.0	33.1	4.23×10^{-2}
5_1. Intensively weathered mudstone	52	20.6	—	—	—	—

Table 2: Onsite TRD trial wall parameters.

Wall label	Depth of wall (m)	Cement content (%)	W/C ratio
SC1	10	11	1.0
SC2	10	14	1.0
SC3	10	17	1.0
SC4	10	20	1.0
SC5	50.5	8	1.0

Table 3: Unconfined compressive strength of cement soil.

Sampling depth/m	Soil layer	Unconfined compressive strength (MPa)				
		SC5 (8%)	SC1 (11%)	SC2 (14%)	SC3 (17%)	SC4 (20%)
0~2	Miscellaneous fill	0.81	1.24	1.36	1.49	1.52
2~4	Silty clay	1.12	1.47	1.58	1.71	1.83
4~6		1.08	1.44	1.60	1.52	1.74
6~8	Silt mixed with silty sand	1.21	1.53	1.71	1.99	2.03
8~10		1.32	1.66	1.89	2.53	3.21
Avg.		1.108	1.468	1.628	1.848	2.066
Variance		0.036	0.023	0.038	0.185	0.443

Figure 1. When the amount of cement is large in cement-mixed soil, the specimen tends to appear off-white, the surface and integrity of which is smooth and good. In contrast, the color is close to the original one, and its integrity is poor.

2.4. Unconfined Compressive Test. The unconfined compressive strength of cement-mixed soil is tested and acquired by compression testing machine with digital display dial. The loading rate of the compression test is controlled at around 0.15 kN/s, and the measure accurate of pressure loading is ensured to 0.01 kN. The results of the unconfined compressive strength test of undisturbed cement-mixed soil are shown in Table 3. The unconfined compressive strength value is mainly subject to the cement amount in cement-mixed soil. The maximum and minimum values, respectively, are 3.21 MPa and 0.81 MPa, which meet the requirements of unconfined compressive strength in the *Specification for mix proportion design of cement soil* (JGJ/T 233-2011) [26] that the standard value of unconfined compressive strength about the 28-days borehole core specimen is not less than 0.8 MPa. To those specimens in a single borehole core, no matter what the amount of mixed cement, the unconfined compressive strength of undistributed cement-mixed soil increases with the sampling depth of borehole core. Obviously, the differences in the sampling depth are more or less affected by the mixed soil properties, but the difference of cement amount in cement mixing.

In the onsite wall test, the relationship between the unconfined compressive strength and the cement ratio at the same sampling depth is shown in Figure 2. With the increase of sampling depth, the unconfined compressive strength of the cement-mixed soil tends to increase. The main reason might be the variation of stratum from fill stratum to deep sandy soil along the 10 m depth of diaphragm wall. Within the range of 20% cement content, there are some differences in the variation tendency at different depths. The solidification effect of the cement-mixed soil in the silty layer about 8 to 10 m deep was relatively superior. Therefore, the impact of soil property on the solidification of cement-mixed soil should be taken seriously, which is extremely significant to evaluate the construction quality and engineering performance of TRD.

Figure 1: Core-drilling sampling of TRD trial walls: (a) SC4; (b) SC5.

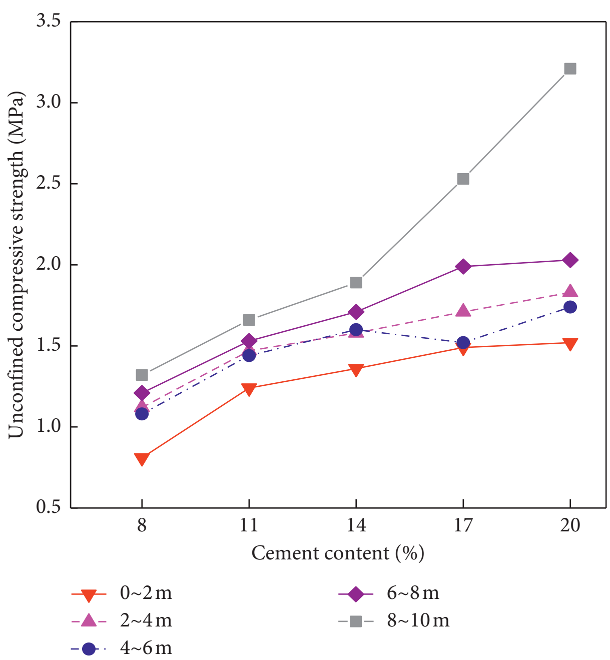

Figure 2: Influence of cement content on the unconfined compressive strength.

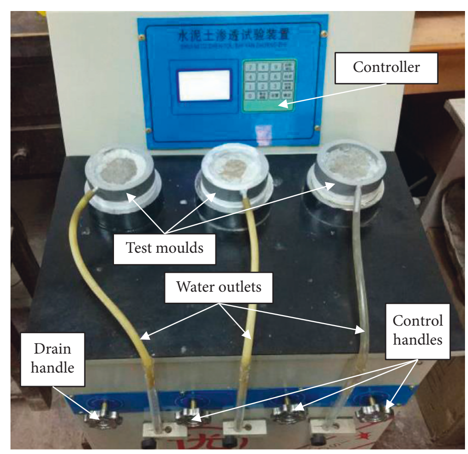

Figure 3: Cement soil permeability test device.

2.5. Permeation Test. The specimens of the permeation test uses 16% minimum cement ratio and 1.0 water cement ratio. According to the *Specification of Soil Test* (SL237-1999) [27], the block of the specimen should be a cylinder with a diameter of 7.5 cm and a height of 3 cm. The permeation test uses a TJSS-25 permeation test device as shown in Figure 3. The device satisfies the experimental requirements of *Specification for mix proportion design of cement soil* (JGJ/T 233-2011) [26], which can measure the permeability coefficient of cement soil under the condition of weak-permeable or impermeable. Liquid paraffin was used in the waterproof in the side wall of the test chamber and applied to the side wall of the test chamber and then kept statically until the paraffin freezes. In order to ensure the reliability of waterproof, the PTFE tape was used in the connection thread between the test chamber and the instrument pipe.

The permeability coefficient of undisturbed cement-mixed soil at different sampling depth is shown in Table 4, which varies between 6.7×10^{-6} cm/s and 4.23×10^{-5} cm/s. Except the No. 2 layer stratum (silty clay), the permeability coefficient of cement-mixed soil is significantly lower than that of the original soil at the corresponding stratum. The permeability coefficients of cement-mixed soil at different sampling depths have significant differences from each other. The permeability coefficients of cement-mixed soil at sandy soil stratum are reduced at most to 3 orders of magnitude. The permeability coefficients of cement-mixed soil at silty clay stratum are the least of them at all the

Table 4: Permeability coefficient of cement-mixed soil.

No.	Soil layer	Permeability coefficient of original soil $\times 10^{-6}$ cm/s	Permeability coefficient of mixed-soil cement $\times 10^{-6}$ cm/s
1	Filing soil	1500	20.8
2	Silty clay	39.2	42.3
3	Silt mixed with silty sand	124	22
4	Silty sand	2670	13.6
5	Fine sand I	5280	9.8
6	Fine sand II	5560	6.7
7	Coarse sand with gravel	42300	12.7

stratums; however, it has risen slightly instead of falling related to silty clay at the original stratum. It is because the mixed soil significantly has changed the microstructure and material composition of the original stratum.

2.6. Discussion on TRD Stirring Performance. Referenced from existing researches about mixing cement and single soil, mixing cement has obvious reinforcement effect on various types of soils. Moreover, the solidification effect of cement to sandy soil is better than that to silty clay. Cement-mixed soil changes the microstructure and material composition of all the stratums due to vertical mixing of all the stratums in TRD. For example, when sandy soil is mixed into silty clay, the disturbance of mixing two types of soil destroyed the inherent structure of the undisturbed soil to some extent. This is why the permeability coefficients of cement-mixed soil at silty clay stratum are the least of them at all the stratums; however, it has risen slightly instead of falling related to silty clay at the original stratum.

In Table 4, there is another obvious feature that the permeability coefficient of original soil increases gradually with sampling depth and the permeability coefficient of cement-mixed soil decreases gradually with sampling depth. After mixing the cement in TRD, the antipermeability of fine sandy soil stratum is better than that of other stratums. In Table 3, the variance of unconfined compressive strength is relatively small as the amount of cement in TRD is small. It demonstrates that the stirring effect of TRD is so good in vertically mixing all the stratums. The variance of unconfined compressive strength is relatively large as the amount of cement in TRD is large. It demonstrates that there is a big difference in the unconfined compressive strength of different soil layers with the increase of cement content due to the precipitation of cement paste. To some extent, this also explains why the solidification effect of sandy soil in deeper stratum is better anyway.

3. Remoulded Cement-Mixed Soil Test

3.1. Particle Size Analysis. The particle composition of soil is one of important indicators of soil properties. Wet particle size analysis was used to analyse the particle size of soil specimens by a Microtrac S3500 laser particle size analyser as shown in Figure 4. The results of particle size analysis for fine sandy, silty clay, and clay in the corresponding stratum are shown in Table 5, and three grading curves are shown in Figure 5. In three grading curves, the grading curve of fine sandy specimen is closest to the fuller grading curve [28], and the grading curve of silty clay and clay are most distant from the Fuller grading curve.

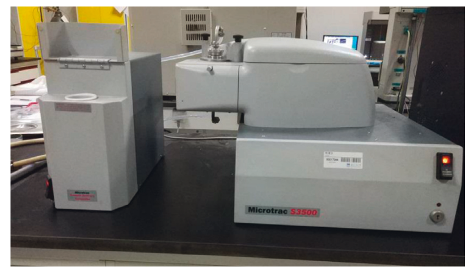

Figure 4: Microtrac S3500 laser particle size analyzer.

3.2. Preparation of the Specimen. 42.5 grade ordinary Portland cement is used in the cement-mixed soil specimen in the light of water-cement ratio of 1.2. According to *Specification for mix proportion design of cement soil* (JGJ/T 233-2011) [26], the specimens with cubic (7.07 cm) are applied in the unconfined compressive strength test, and the specimens with circular cone (7 cm in upper diameter, 8 cm in lower diameter, and 3 cm in height) are applied in the permeability test. Three parallel specimens had been prepared for each specification.

The preparation process of cement-mixed soil is listed as follows: (1) The quality of soil, cement, and water in cement-mixed soil is calculated according to the ratio of cement and soil. (2) Soil and cement are mixed evenly, and then water is added and stirred until the mixture is evenly mixed. The stirring time is approximately controlled between 10 and 20 min. (3) The moulding of specimen uses the tamping and filling modes which shall be controlled within 25 minutes. (4) The specimens dismantled the mould at room of temperature (20 ± 5°C) and the relative humidity being not less than 50% and then are cured in the standard maintenance chamber (relative humidity being more than 95% and temperature being 20 ± 3°C) until the prescribed period.

3.3. Test Programme. According to the stratum position of engineering site, the fine sand, silty clay, and clay were mixed according to different mixing ratios as shown in Table 6 for imitating the cement-mixed soil at different stratums in TRD.

Table 5: Results of soil particle size analysis.

Soil specimen	Particle size composition (%)				
	2000~500 μm	500~250 μm	250~75 μm	75~5 μm	<5 μm
Clay	0	1.23	19.31	39.24	40.22
Silty clay	0	0.38	15.15	79.72	4.75
Fine sand	0.5	26.8	62.8	9.9	0

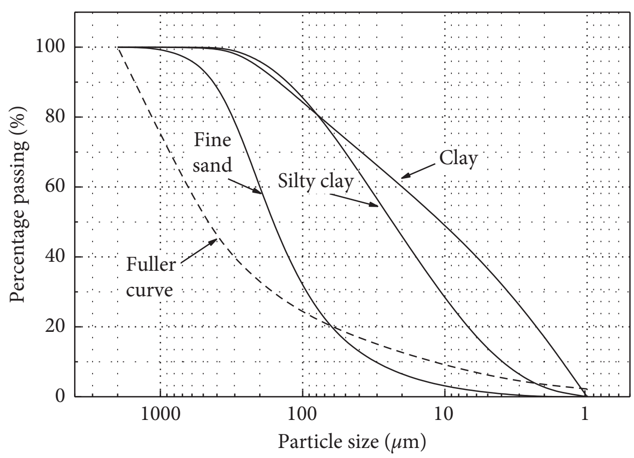

Figure 5: Gradation curve of three soil specimens.

Table 6: Composition of mixed soil specimens.

No.	Composition of mixed soil	Cement content (%)	Age (days)
1	Fine sand	20	28
2	Silty clay	20	28
3	Clay	20	28
4	75% fine sand + 25% silty clay	20	28
5	50% fine sand + 50% silty clay	20	28
6	25% fine sand + 75% silty clay	20	28
7	50% clay + 50% silty clay	20	28
8	50% clay + 50% fine sand	20	28

3.4. Unconfined Compressive Strength and Permeability Coefficient. The results of unconfined compressive test and permeability test about cement-mixed soil under different test programs are listed in Tables 7 and 8. The unconfined compressive strength and permeability coefficient under different test programs are markedly different, which are mainly related to the microstructure and material composition of cement-mixed soil and the cement content.

The unconfined compressive strength, permeability coefficient, and the mixture ratios of cement-mixed fine soil and cement-mixed silty clay are shown in Figure 6. The engineering performance of two types of cement-mixed soil does not change regularly with the mixture ratio of mixed soil. Unconfined compressive strength: the best ratio of mixed soil corresponding to the highest strength is 75% fine sand and 25% silty clay. Permeability coefficient: the permeability coefficient of cement-mixed soil is roughly distributed between cement-mixed fine sandy and cement-mixed silty clay. When the mixture ratio of 25% fine sand

Table 7: Unconfined compressive strength of mixed-soil cement.

Mixed-soil specimen	Collapse load (kN)			Unconfined compressive strength (MPa)			
	1	2	3	1	2	3	Avg.
100% clay	13.12	13.57	12.89	2.62	2.71	2.58	2.64
100% silty clay	9.7	10.12	8.77	1.94	2.02	1.75	1.91
100% fine sand	21.89	21.75	22.64	4.38	4.35	4.53	4.42
75% fine sand + 25% silty clay	34.56	33.89	33.51	6.91	6.78	6.70	6.80
50% fine sand + 50% silty clay	12.82	13.72	13.19	2.56	2.74	2.64	2.65
25% fine sand + 75% silty clay	10.12	10.34	10.57	2.02	2.07	2.11	2.07
50% clay + 50% silty clay	13.72	13.12	13.5	2.74	2.62	2.70	2.69
50% clay + 50% fine sand	11.13	11.39	10.64	2.23	2.28	2.13	2.21

and 75% silty clay is used, the permeability coefficient of cement-mixed soil decreased by 26% compared with that of cement-mixed fine sandy soil, but it is 1.91 times higher than cement-mixed silty clay, which concludes that the material components with higher permeability play a dominating role in the permeability of cement-mixed soil.

Figure 7 demonstrates the unconfined compressive strength and the permeability coefficient of cement-mixed soil with different mixing relationships. When the content of two types soil in mixed soil is equivalence. Unconfined compressive strength: the strength of cement-mixed clay and silty clay is close to the bigger strength of the clay; the strength of cement-mixed fine sandy and clay is less than any of the two types of soil, and the strength of cement-mixed fine sandy and silty clay is fallen in between the strength of cement fine sandy and the strength of cement silty clay. Permeability coefficient: the permeability law of cement-mixed soil with different soils is similar that the permeability of cement-mixed soil is controlled by the permeability of the soil in mixed soil.

4. Microstructure Analysis of Cement-Mixed Soil

4.1. Particle Analysis of Mixed Soil. One of the obvious changes between mixed soil and single soil is different soil grading which is an important index affecting the porosity and bulk density of soil. The bulk density of cement-mixed soil directly determines its compactness and porosity, and the appropriate particles grading curve is crucial to the mechanical properties of cement-mixed soil with compact

Table 8: Permeability coefficient of mixed-soil cement.

Mixed-soil specimen	Permeability coefficient ($cm \cdot s^{-1}$) 1	2	3	Avg.
100% clay	7.92×10^{-9}	8.52×10^{-9}	1.07×10^{-8}	9.06×10^{-9}
100% silty clay	1.13×10^{-7}	8.51×10^{-8}	1.20×10^{-7}	1.06×10^{-7}
100% fine sand	3.20×10^{-7}	5.33×10^{-7}	4.07×10^{-7}	4.20×10^{-7}
75% fine sand + 25% silty clay	4.12×10^{-7}	3.73×10^{-7}	3.91×10^{-7}	3.92×10^{-7}
50% fine sand + 50% silty clay	3.46×10^{-7}	3.04×10^{-7}	4.03×10^{-7}	3.51×10^{-7}
25% fine sand + 75% silty clay	2.86×10^{-7}	2.93×10^{-7}	3.51×10^{-7}	3.10×10^{-7}
50% clay + 50% silty clay	1.01×10^{-7}	8.21×10^{-8}	7.85×10^{-8}	8.72×10^{-8}
50% clay + 50% fine sand	1.63×10^{-7}	3.01×10^{-7}	3.46×10^{-7}	2.70×10^{-7}

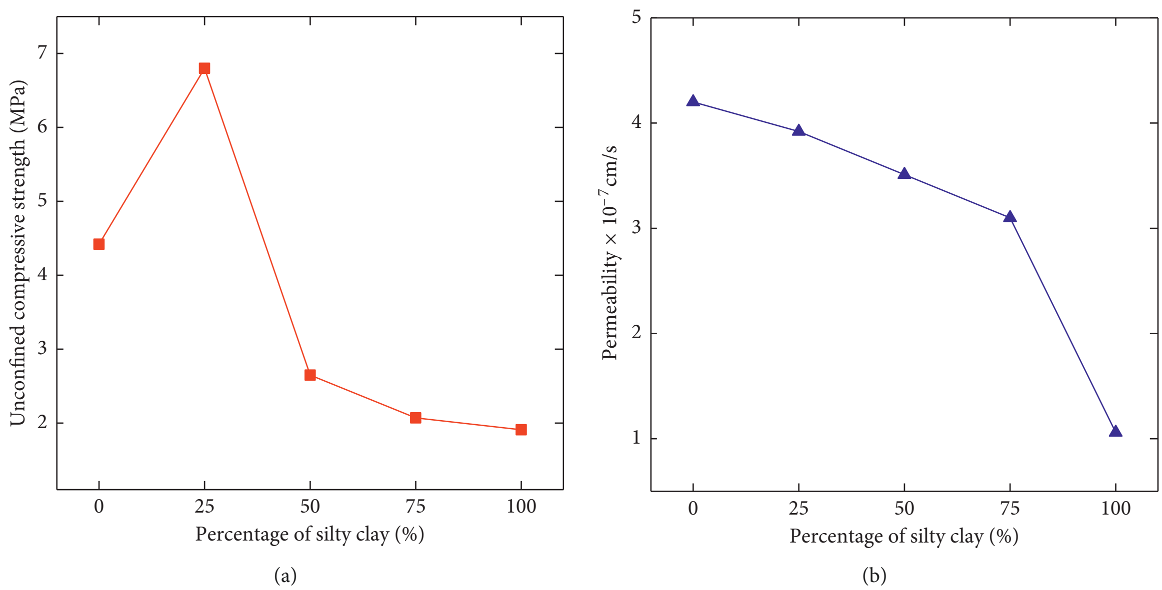

Figure 6: Results of fine sand and silty clay mixed-soil cement: (a) unconfined compressive strength; (b) permeability coefficient.

microstructure filled into coarse grain pore by fine grain pore [29]. Fuller put forward the evaluation method of the maximum density curve of granular mixture [28]. According to various incorporation ratios of mixed soil, the approximate results of particles component of mixed soil are shown in Table 9.

Figure 8 demonstrates the grading curves of mixed soil. Figure 8(a) demonstrates the grading curve of mixed fine sandy soil and silty clay. When 25% silty clay is mixed into the fine sandy soil as shown in Gradation 1, the tail of grading curve almost coincides with Fuller curve. This is because the particles of silty clay are mainly composed of particles below 0.075 mm, and the addition fine sandy soil is equivalent to adding the content of particles below 0.075 mm, so that its grading curve is closer to that of Fuller curve, which also explains that the unconfined compressive strength increases significantly under the corresponding conditions. When the content of silty clay mixed into the fine sandy soil increases to 50% as shown in Gradation 2, the content of the particles below 0.075 mm in mixed soil would reach to nearly 50% and the grading curve of mixed soil deviates from Fuller curve. Meanwhile, the unconfined compressive strength reduces significantly under the corresponding conditions. Similarly, there is a coincident rule as shown in Gradation 3. Therefore, the grading curve of mixed soil containing sandy soil is closer to the Fuller curve, which can improve the unconfined compressive strength of cement-mixed soil. Figure 8(b) demonstrates the grading curve of mixed clay and silty clay that is between the grading curve of clay and the grading curve of silty clay as shown in Gradation 4. Although the grading curve of silty clay is the closest to the Fuller curve, the unconfined compressive strength of cement-mixed silty clay is the lowest of all cement-mixed soils. This is because that the high content of fine grain in clay and the large aggregates formed by the strong cohesive among the fine grains cause the corresponding grading curve to move forward. Therefore, gradation analysis is not applicable to the cement-mixed soil containing the clay. Figure 8(c) demonstrates the grading curve of mixed sandy soil and clay. Similarly, the grading curve of clay deviates from the Fuller curve more than Gradation 5, but the unconfined compressive strength of clay is greater than that of cement-mixed soil.

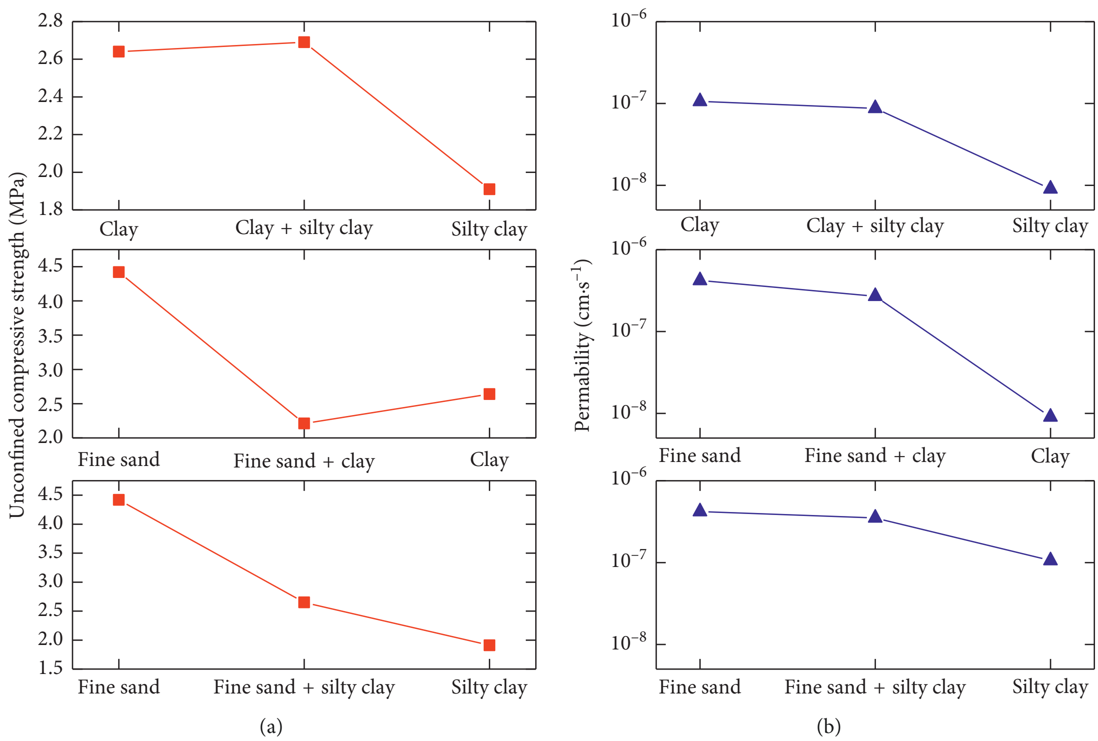

Figure 7: Test results of mixed-soil composition: (a) unconfined compressive strength; (b) permeability coefficient.

Table 9: Percentage of different particle sizes.

No.	Soil specimen	Particle size (μm)				
		2000~500	500~250	250~75	75~5	<5
Gradation 1	75% fine sand + 25% silty clay	0.38	20.20	50.89	27.36	1.19
Gradation 2	50% fine sand + 50% silty clay	0.25	13.59	38.98	44.81	2.38
Gradation 3	25% fine sand + 75% silty clay	0.13	6.99	27.06	62.27	3.56
Gradation 4	50% clay + 50% silty clay	0.00	0.81	17.23	59.48	22.49
Gradation 5	50% clay + 50% fine sand	0.25	14.02	41.06	24.57	20.11

4.2. Microstructural Analysis. The scanning electron microscope was used to observe the microstructure of mixed-soil cement specimens under the magnification of 3000 and 10000 times. The 3D microstructure analysis has been implemented by 2D SEM images of cement-mixed soil using a professional image analysis software of *Image-Pro Plus* [30]. The analysis procedure is listed in detail as follows:

(1) Scale calibration: the measuring scale of the scanning process is used to calibrate the SEM image.

(2) Image binaryzation: *Image-Pro Plus* software can generate a binary grayscale image by the AOI (area of interest) parameters, and the AOI threshold is set to 100.

(3) Image segmentation: the disconnectivity of target image tile is detected by the *Image-Pro Plus* software.

(4) Microstructure parameters measurement of average pore area, porous, porosity, average pore size, and pore width are used as take average pore area, pore counting, porosity, average pore size, and pore width as the microstructure parameters. The extraction effects of AOI are shown in Figure 9.

The microstructure parameters of cement-mixed soil specimens and the normalized microstructure parameters are shown in Table 10. The microstructure parameter comparisons of mixed-soil cement as shown in Figure 10 indicate that (i) to cement-mixed fine sandy soil and silty clay, with the increase in the content of silty clay, the microstructure parameters generally decrease. The permeability coefficient of cement-mixed soil also decreases accordingly, which demonstrates that the results of macroscopic and microscopic test are consistent; (ii) to cement-mixed clay and silty clay, there is not much difference of microstructure parameters between cement-mixed two types soil and cement-mixed silty clay when the amount ratio of clay and silty clay equals to 1 : 1. Meanwhile, the microstructure parameters of cement-mixed clay are significantly lower than those of cement-mixed silty clay, and cement-mixed clay and silty clay; (iii) to cement-mixed clay and fine sandy soil, when the amount ratio of clay and fine

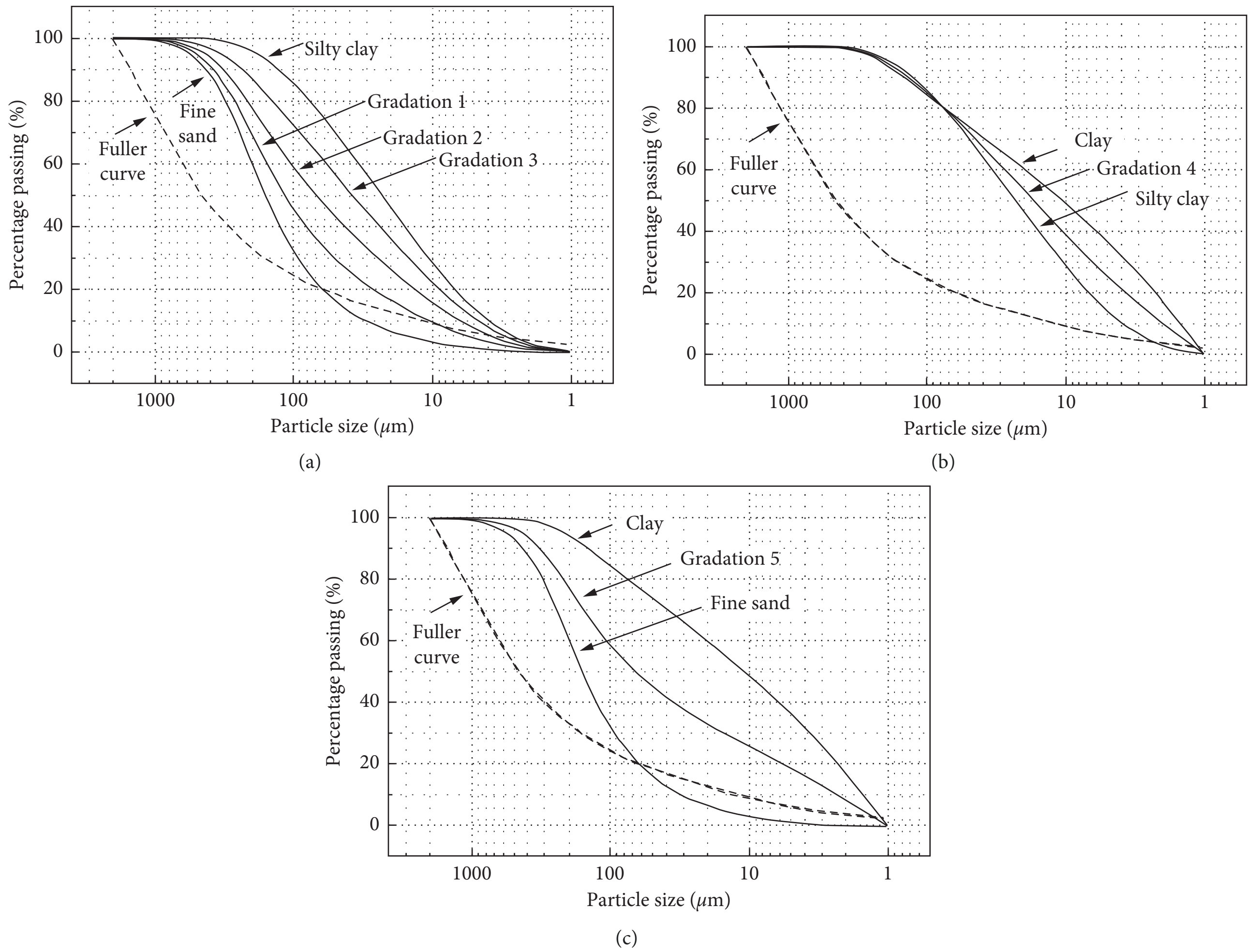

Figure 8: Particle size distribution curves of mixed soil: (a) fine sand and silty clay; (b) clay and silty clay; (c) clay and fine sand.

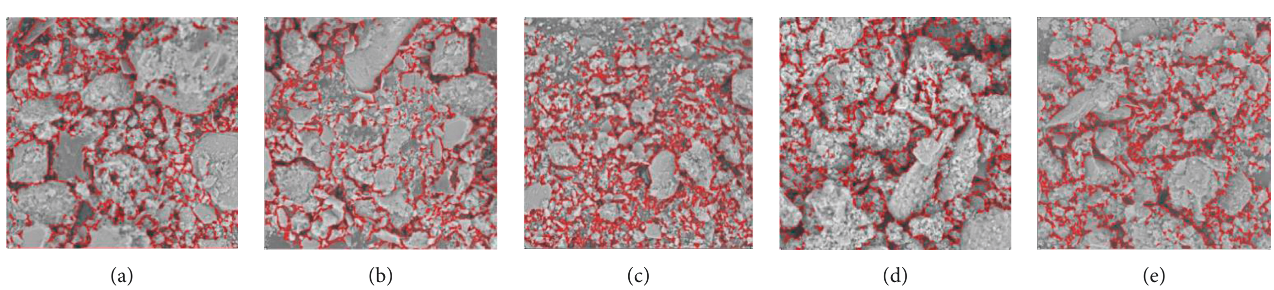

Figure 9: Selection of AOI area and the effect of image processing: (a) 75% fine sand + 25% silty clay; (b) 50% fine sand + 50% silty clay; (c) 25% fine sand + 75% silty clay; (d) 50% clay + 50% silty clay; (e) 50% clay + 50% fine sand.

sandy soil equals to 1 : 1, except the pore width, other three microstructure parameters are between the microstructure parameters of cement-mixed fine sandy soil and cement-mixed clay.

5. Discussion

The undisturbed cement-mixed soil test in TRD indicates the curing effect of sand is better than that of soil in other stratum. The strength of the underlying silty soil with silty sand is higher than that of surface filling soil and silty clay after curing. The permeability improvement of cement soil in sandy stratum is also the highest. Different stirring methods of cement soil will affect the performance of cement soil compared from TRD to DMP.

In mesoscopic, cement fine sand has a large pore structure, and the average pore area is 2.46 times the cement clay. The incorporation of fine grain into the mixed soil will affect the generation of fibrous cement hydrates, while the incorporation of a certain amount of fine grain into sand soil

Table 10: Image analysis results of microstructure parameters.

Soil specimen	Average pore area (μm^2)	Total pore area (μm^2)	Porosity	Average aperture (μm)	Pore width (μm)
Fine sand	4.6045	1533.2915	0.1880	1.8785	0.9332
Silty clay	2.9966	1450.3719	0.1779	1.5638	0.7768
Clay	1.8685	1100.5638	0.1350	1.4379	0.7850
75% fine sand + 25% silty clay	3.8862	1523.3817	0.1868	1.6530	0.8393
50% fine sand + 50% silty clay	3.3847	1455.4369	0.1785	1.6548	0.7768
25% fine sand + 75% silty clay	3.0509	1501.0603	0.1841	1.7163	0.8247
50% clay + 50% silty clay	3.3346	1320.4958	0.1619	1.6086	0.7888
50% clay + 50% fine sand	3.7485	1270.7429	0.1558	1.8229	0.8184

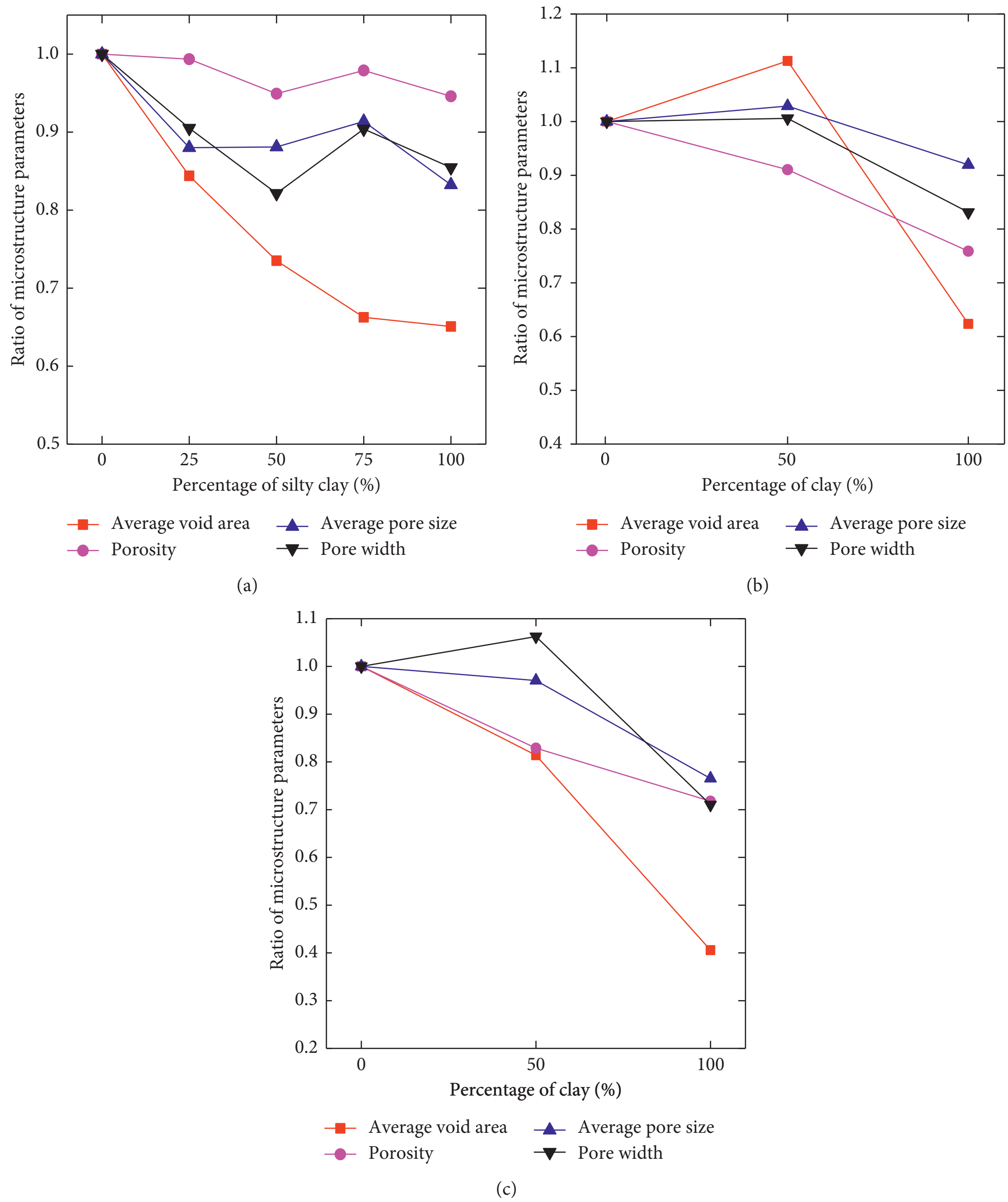

Figure 10: Comparison of mixed-soil cement microstructure parameters: (a) fine sand + silty clay; (b) clay + silty clay; (c) clay + fine sand.

will weaken the generation of cement soil strength, resulting in the reduction of unconfined compressive strength of cement soil. The incorporation of fine sand is generally more conducive to the development of microstructure of cement-mixed soil, which is not conducive to the impermeability of cement soil.

6. Conclusion

The results of the undisturbed cement-mixed soil test indicate that soil property has a substantial influence on the mechanics and penetrability of cement-mixed soil. The treatment effect of sandy soil in TRD is better than that of other soil. When the variance of unconfined compressive strength is relatively small as the amount of cement in TRD is small, it demonstrates that the stirring effect of TRD is so good to vertically mix all the stratums. When the variance of unconfined compressive strength is relatively large as the amount of cement in TRD is large, it demonstrates that there is a big difference in the unconfined compressive strength of different soil layers with the increase of cement content due to the precipitation of cement paste.

The unconfined compressive strength of cement-mixed soil is closely related to the gradation of mixed soil. When the grading curve of mixed soil is close to the Fuller curve, the soil compactness and the unconfined compressive strength of cement-mixed soil increase. When the grading curve of mixed soil deviates from the Fuller curve, the unconfined compressive strength of cement-mixed soil decreases accordingly. The permeability coefficient of cement-mixed soil is affected by one of the stronger permeabilities of the mixed soil. The incorporation of fine grain into mixed soil will affect the formation of fibrous cement hydrates, while the incorporation of a certain amount of fine grain into sandy soil will affect the formation of cement-mixed soil strength, resulting in the reduction of unconfined compressive strength of the cement-mixed soil. In terms of microstructure, the incorporation of fine sand is more conducive to the development of the microstructure of cement-mixed soil but is not conducive to the ant-permeability of cement-mixed soil.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[1] P. Zhang and R. Liu, "The application of SMW method in foundation pit," *Chinese Journal of Rock Mechanics and Engineering*, vol. 19, no. 1, pp. 1104–1107, 2000, in Chinese.

[2] A. Zhang and J. Wu, "Development and application of TRD method for construction of underground continuous wall," *Water Resources and Hydropower Engineering*, vol. 45, no. 9, pp. 75–77, 2014, in Chinese.

[3] J. Huo, J. Zhu, Z. Hu et al., "Application of deep mixing cement soil mixing wall (CSM)," *Chinese Journal of Geotechnical Engineering*, vol. 34, no. s1, pp. 666–670, 2012, in Chinese.

[4] M. Sakuma, "Mixing cement-soil wall in the original position," *BAUER Construction Method Research Association*, 2008, in Japanese.

[5] M. A. Ismail, H. A. Joer, W. H. Sim, and M. F. Randolph, "Effect of cement type on shear behavior of cemented calcareous soil," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 128, no. 6, pp. 520–529, 2002.

[6] S. C. Chian, "Tailoring the properties of cement-treated clayey soils," in *Geotechnical Design and Practice*, K. Ilamparuthi and R. G. Robinson, Eds., pp. 173–182, Springer, Singapore, 2019.

[7] K. Yao, Q. Chen, J. Ho, H. Xiao, and F. H. Lee, "Strain-dependent shear stiffness of cement-treated marine clay," *Journal of Materials in Civil Engineering*, vol. 30, no. 10, article 04018255, 2018.

[8] N. Miura, S. Horpibulsuk, and T. S. Nagaraj, "Engineering behavior of cement stabilized clay at high water content," *Soils and Foundations*, vol. 41, no. 5, pp. 33–45, 2001.

[9] S. Horpibulsuk, N. Miura, and T. S. Nagaraj, "Clay-water/cement ratio identity for cement admixed soft clays," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 131, no. 2, pp. 187–192, 2005.

[10] C. Liu and R. D. Starcher, "Effects of curing conditions on unconfined compressive strength of cement- and cement-fiber-improved soft soils," *Journal of Materials in Civil Engineering*, vol. 25, no. 8, pp. 1134–1141, 2013.

[11] N. C. Consoli, S. F. V. Marques, N. C. Sampa et al., "A general relationship to estimate strength of fibre-reinforced cemented fine-grained soils," *Geosynthetics International*, vol. 24, no. 4, pp. 435–441, 2017.

[12] G. A. Miller and S. Azad, "Influence of soil type on stabilization with cement kiln dust," *Construction and Building Materials*, vol. 14, no. 2, pp. 89–97, 2000.

[13] I. Tomac, W. F. Vanimpe, R. D. V. Flores, and P. Menge, "Binder-soil interaction in cement deep mixing through SEM analysis," in *Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering*, pp. 1265–1268, Rotterdam Millpress Science Publishers, Osaka, Japan, September 2005.

[14] H. Xiao, F. H. Lee, and K. G. Chin, "Yielding of cement-treated marine clay," *Soils and Foundations*, vol. 54, no. 3, pp. 488–501, 2014.

[15] H. Xiao, W. Shen, and F. H. Lee, "Engineering properties of marine clay admixed with Portland cement and blended cement with siliceous fly ash," *Journal of Materials in Civil Engineering*, vol. 29, no. 10, article 04017177, 2017.

[16] B. Shi, Z. Liu, Y. Cai, and Z. Xiaoping, "Micropore structure of aggregates in treated soils," *Journal of Materials in Civil Engineering*, vol. 19, no. 1, pp. 99–104, 2007.

[17] K. Lemaire, D. Deneele, S. Bonnet, and M. Legret, "Effects of lime and cement treatment on the physicochemical, microstructural and mechanical characteristics of a plastic silt," *Engineering Geology*, vol. 166, pp. 255–261, 2013.
[18] E. Mengue, H. Mroueh, L. Lancelot, and R. Medjo Eko, "Physicochemical and consolidation properties of compacted lateritic soil treated with cement," *Soils and Foundations*, vol. 57, no. 1, pp. 60–79, 2017.
[19] Q. Wang, H. Chen, and K. Cai, "Quantitative evaluation of microstructure features of soil contained some cement," *Rock and Soil Mechanics*, vol. 23, no. s1, pp. 12–16, 2003, in Chinese.
[20] L. Yin, X. Chen, and F. Wang, "Research on the microstructure and improvement mechanic of cement-mixed soft soil," *Journal of Central South Highway Engineering*, vol. 32, no. 2, pp. 159–161, 2007, in Chinese.
[21] P. Han, X. Liu, and X. Bai, "Effect of sodium sulfate on strength and micropores of cemented soil," *Rock and Soil Mechanics*, vol. 35, no. 9, pp. 2555–2561, 2014, in Chinese.
[22] F. Yu, Y. Huang, and D. Sun, "Modification effect of lime soil and cement soil by water-reducing agent," *Journal of Building Materials*, vol. 20, no. 2, pp. 283–287, 2017, in Chinese.
[23] X. Huang and G. Zhou, "Hardening mechanism of cement-stabilized soil," *Chinese Journal of Geotechnical Engineering*, vol. 16, no. 1, pp. 62–68, 1994, in Chinese.
[24] J. Li, Z. Zhao, and G. Gao, "Analysis and microstructure characters of cement-soil," *Journal of Chengdu University of Technology*, vol. 27, no. 4, pp. 388–393, 2000, in Chinese.
[25] P. Ding and Q. Zhang, "Swelling tests of cement-treated dredged sediment and analyses of its mineralogical mechanisms," *Journal of Tongji University*, vol. 30, no. 9, pp. 1083–1086, 2002, in Chinese.
[26] Ministry of Housing and Urban-Rural Construction of the People's Republic of China, *JGJ/T 233-2011 Specification for Mix Proportion Design of Cement Soil*, China Architecture & Building Press, Beijing, China, 2011, in Chinese.
[27] Ministry of Water Resources of the People's Republic of China, *SL237-1999 Specification of Soil Test*, Nanjing Hydraulic Research Institute, Nanjing, China, 1999, in Chinese.
[28] F. Lange, H. Mörtel, and V. Rudert, "Dense packing of cement pastes and resulting consequences on mortar properties," *Cement and Concrete Research*, vol. 27, no. 10, pp. 1481–1488, 1997.
[29] X. Tan, M. Shen, and Q. Zhang, "Particle size analysis of clay by malvern laser particle analyzer," *Journal of Civil, Architectural & Environmental Engineering*, vol. 33, no. 6, pp. 96–100, 2011, in Chinese.
[30] X. Zhang, T. Huang, Y. Zhang et al., "Image-pro plus analysis of pore structure of concrete," *Journal of Building Materials*, vol. 18, no. 1, pp. 177–182, 2015, in Chinese.