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Research Article

Study on Compaction of Reclaimed Soil of Nonmetallic Mining Area in Northern Foothills of Tianshan Mountains in Xinjiang, China

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This study focused on the changes of the compaction of the reclaimed soil after the reclamation process and the one-year maintenance period of the nonmetallic mines in north foothills of Tianshan Mountains in Xinjiang. The plate load experiment method was employed to simulate the compaction effect of various times of compaction from the reclamation machine on a different thickness of the reclaimed soil. The experimental data were analyzed by multivariate statistical analysis. The experimental results showed both compaction frequency and thickness of the reclaimed soil were key factors affecting the compaction of the reclaimed soil, and the interaction between them had a dramatic impact on the soil compaction. The difference of the porosity between the three-time compacted soil by the compaction machine and the noncompacted soil was significant. The effect of a single compaction dampened with the increasing times of compaction. The porosity of the 50 cm and 70 cm thick topsoil continuously decreases with the increasing times of compaction at the depth of 10 cm from the surface soil. The porosity at the 30 cm depth of the 50 cm and 70 cm thick topsoil decreased first and then increased with the increasing times of compaction. At the end of the one-year maintenance period, samples from different depths of the reclaimed soil of various thicknesses were collected to investigate the changes of porosity. The results showed the porosity of the reclaimed soil at different depths was changed due to irrigation. The porosity of the uncompacted soil decreased progressively from the surface to the deep region. The porosity of the compacted soil at the 10 cm depth was lower than that at the 30 cm depth due to soil sealing, whereas the porosity decreased with the increasing depth in the deeper region. The results from this study could provide a fundamental reference for the reclamation of nonmetallic mines in northern foothills of Tianshan Mountains in Xinjiang, China.

1. Introduction

The northern foothills of Tianshan Mountains in Xinjiang are one of the key developmental and constructional areas of the national "Belt and Road" initiative. The area is rich in nonmetallic minerals (limestone, dolomite, marble, granite, and gravel). There were about 260 nonmetallic mining permits issued by the Department of Land and Resources of the Autonomous Region, which accounted for 58% of the total number of permits issued in Xinjiang. The massive exploitation of mineral resources will inevitably cause extensive damages to the local geological and ecological environment, resulting in the large-scale destruction of land resources and vegetation on the surface. According to incomplete statistics, the open-pit mining of nonmetallic mines in this region had resulted in the destruction of about 555 km^2 of land resources, not including the sandstone ores managed by various counties and cities. The nonmetallic mining is done using the open-pit mining approach. After mining, the large-scale mining pits and tremendous amounts of massive waste rocks remain, which will excavate and occupy a considerable amount of land resources (Figures 1 and 2). After the accomplishment of mining, the reclamation of the mined land will be carried out. The topsoil is an integral part to reclaim the mining area into a grassland or a forest zone. During the course of

Figure 1: Open-pit mining area.

Figure 2: Waste rock piles.

land reclamation, the reclamation machine will inevitably have an impact of compaction on the topsoil. When the one-year maintenance period is over, the degree of compaction of the topsoil would be changed. All these changes will affect the quality of the reclamation soil, which, in turn, influences the degree of ecological restoration of vegetation on the surface of the mining area.

Recently, studies on the soil compaction and the degree of compaction have yielded fruitful results, such as the impact of compaction on the water content of soil [1–7], the changes of physical and chemical properties of the reclaimed soil after compaction [8–16], the effect of compaction on water infiltration in soil [17], the effect of compaction on the soil structure [18, 19], studies of the soil compaction using different reclamation materials [20–22], and assessment methods of the quality of the reclaimed soil [23, 24]. The drop weight test was mainly used for the on-site simulation of the impact of the reclamation soil compaction in the mechanical compaction process [25–27]. According to the past results, it was found that studies on the compaction of soil were mostly concentrated in the agricultural field, and the compaction study of the reclaimed soil in the mining area was mostly focusing on the soil reclamation in the coal mining area. The drop weight test was mainly used to simulate the compaction effect of various machines. However, it is still elusive to utilize the plate load test to simulate the compaction effect of the reclaimed soil of a different thickness filled with large blocks of hard waste rocks in the nonmetallic mines area.

In view of the limitations of the past studies and the unique characteristics of the sandy soil of the nonmetallic mining zone, this study simulated the compaction effect of reclamation machinery on the reclaimed soil by the in situ plate load experiment method. The in situ sampling, indoor geotechnical experiments, and mathematical statistical analysis methods were used to study the compaction effect of compaction machinery to the reclaimed topsoil and the porosity change of the reclaimed soil after the one-year maintenance period.

2. Experimental Materials and Methods

2.1. Experimental Materials. This compaction test of the reclaimed soil was performed at the Changji groundwater balance testing ground in Xinjiang. The reclaimed soil sample was taken from a limestone mining area in Dabancheng district, Urumqi, Xinjiang. The reclaimed soil was a sandy brown calcic soil. The bulk density of the reclaimed soil was 12.646 kN/m^3 with 57.71% porosity and 11.76% water content. The lower part of the reclaimed soil was backfilled with waste rocks from this limestone mining area.

2.2. Experimental Design. This experiment was based on statistical principles to apply a 3 × 3 mixed factorial design to establish a simulating experimental area. The hydraulic jack pressure simulation was utilized to analyze the characteristic changes in density and porosity of the reclaimed soil using a compaction machine (crawler-type bulldozer), different compaction times (1 time, 3 times, and 5 times), and different topsoil thickness (30 cm, 50 cm, and 70 cm). The experiment was designed to collect samples at the depths of 10 cm and 35 cm, respectively, to represent the changes in porosity of the reclaimed soil at different depths.

2.3. Experimental Methods. The widely used reclamation machines in Xinjiang are track-type bulldozers. The simulating pressure in this study was the pressure generated by the NT855-B280 track-type bulldozer to the ground. The pressure to the ground from this bulldozer was 33.7 kPa each time. The plate load test approach was used to apply pressure in this experiment, which was different from the conventional drop weight test (Figure 3). The readout of the hydraulic jack was calculated based on the reclamation machine's one-time pressure value to the ground and the plate area. A cylindrical metal barrel with a bottom area of 2 m^2 was used as the testing pit (Figure 4). The depth of the barrel was 2 m. The limestone waste rocks were backfilled at the bottom of the barrel. The upper part of the barrel was backfilled with 30 cm, 50 cm, or 70 cm reclaimed soil according to the initial design. The device used in the plate load test was utilized to compact the topsoil for 1, 3, and 5 times. Three ring-shaped knives were used to take three original samples at the depths of 10 cm and 30 cm, respectively. The base where the experiment was performed had a limited number of test barrels. The six barrels were divided into 2 groups in the test to observe the effect of soil

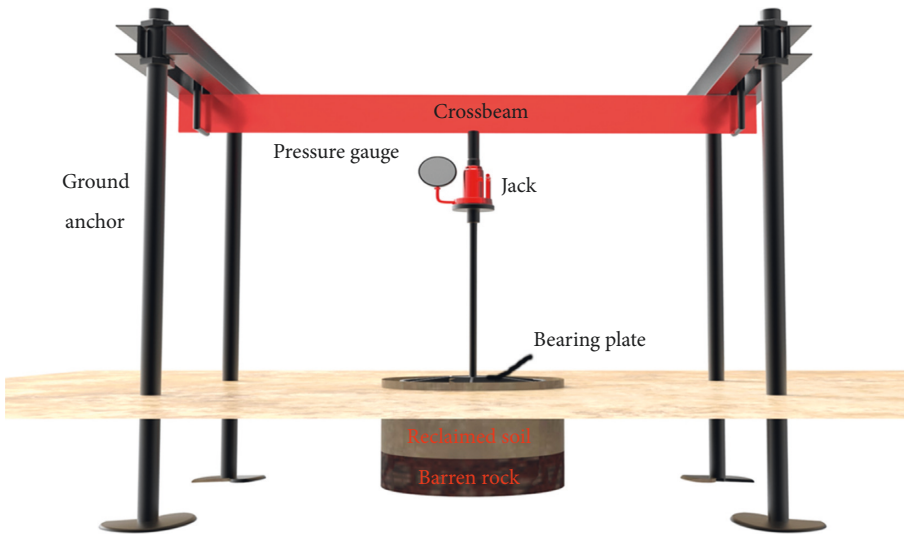

Figure 3: Illustration of the setups in the plate load test.

Figure 4: Cylindrical barrels.

compaction at different depths under different compaction degrees with various thicknesses of topsoil after a one-year maintenance period. One group was backfilled with 30 cm, 50 cm, and 70 cm, respectively, without compaction, whereas the other group was compacted once. The irrigation was performed based on empirical values of irrigation amount and frequency in the Xinjiang region. The amount of irrigation at each time was related to the thickness of the soil. The thicker the soil was, the greater the amount of irrigation would be. After one year, two aluminum boxes and one ring-shaped knife were used to collect samples at the depths of 10 cm, 30 cm, 50 cm, and 70 cm, respectively, according to the differences in topsoil thickness. The relevant analysis was performed indoor.

3. Results and Analysis

3.1. Experimental Data Compiling. A total of 16 groups of 48 soil samples were obtained in the compaction experiment. The topsoil with thickness of 50 cm and 70 cm was divided into 2 layers to collect samples. The topsoil with thickness of 30 cm at the depth of 30 cm could not be sampled as it was the interface between soil and waste rocks. Alternatively, samples at the depth of 10 cm were collected. The results of the compiled experimental data are shown in Table 1.

A total of 18 groups with 54 samples were collected after a one-year maintenance period. The sampling could be done to the depth of the interface between the original soil and the waste rocks. The major reason is that the reclaimed soil had been irrigated over one year with the topsoil subsidence to some degrees along with penetration of some soil particles into the lower waste rocks. The experimental results are summarized in Table 2.

3.2. Analysis of the Compaction Effect of the Reclaimed Soil during Reclamation

3.2.1. Analysis of Factors Affecting the Compaction Effect of the Reclaimed Soil. The results of the porosity in the pre-compaction test (Table 1) were analyzed using SPSS 19.0 software. The analytical results are as follows: the skewness was 1.094 with the standard error of 0.343, and the kurtosis was 2.079 with the standard error of 0.674. These results indicated that the data did not follow the Gauss distribution. The independent sample test in the nonparametric test was used for analysis. The analytical results are shown in Tables 3 and 4. It can be seen from Table 3 that the thickness of the soil layer and times of compaction had remarkable impacts on the porosity, or the compaction degree, of the reclaimed soil, while the depth of the soil sampled has no significant effect. The data from Table 4 show that, under the same compaction, the compaction effect between the topsoil thickness at 70 cm and 30 cm was the most remarked, while

Table 1: Results of the compaction experiment.

Thickness of topsoil (cm)	Times of compaction	Depth of sampling (cm)	Average of natural density, ρ (g/cm^3)	Average of water content in mass, ω (%)	Average of porosity (%)
70	0	10	1.290	11.76	57.71
	1	10	1.425	11.41	53.15
		30	1.455	12.60	52.68
	3	10	1.441	10.58	52.23
		30	1.457	12.29	52.47
	5	10	1.447	9.70	51.70
		30	1.460	14.12	53.09
50	1	10	1.470	14.23	52.87
		30	1.455	11.23	52.07
	3	10	1.486	12.93	51.81
		30	1.483	11.67	51.34
	5	10	1.490	11.17	50.92
		30	1.539	15.01	50.97
30	1	10	1.512	11.72	50.42
	3	10	1.552	13.36	49.83
	5	10	1.556	12.71	49.42

Notes. Only the average value of each experiment was listed. The water content is expressed in mass. The calculation method is that the mass of water in the soil is divided by the mass of dry soil. Calculation formula of the porosity is $n = ((1-\rho)/2.73)/(1+\omega)$.

Table 2: Experimental results of the reclaimed soil after a one-year maintenance period.

Times of compaction	Thickness of topsoil (cm)	The depth of the sampling position (cm)	Average of natural density, ρ (g/cm^3)	Average of water content in mass, ω (%)	Average of porosity (%)
0	30	10	1.389	11.07	54.18
		30	1.543	17.77	52.02
	50	10	1.407	10.98	53.55
		30	1.539	18.22	52.31
		50	1.552	16.10	51.04
	70	10	1.425	10.96	52.96
		30	1.538	18.50	52.45
		50	1.571	17.61	51.08
		70	1.651	14.51	47.18
1	30	10	1.530	9.74	48.93
		30	1.588	17.11	50.33
	50	10	1.495	10.32	50.35
		30	1.548	18.16	52.02
		50	1.491	12.09	51.28
	70	10	1.464	10.46	51.46
		30	1.553	18.45	51.97
		50	1.577	16.47	50.41
		70	1.612	16.17	49.17

Note. Only the averages of each group of experiments are listed.

Table 3: Results of the independent sample test.

No.	Null hypothesis	Analytical method	Significance	Decision
1	The distribution of the porosity is the same regardless of the soil thickness	Kruskal–Wallis test of independent samples	$0.000 < 0.05$	Reject
2	The distribution of the porosity is the same regardless of the compaction times	Kruskal–Wallis test of independent samples	$0.008 < 0.05$	Reject
3	The distribution of the porosity is the same regardless of the depths of sampling	Mann–Whitney U test of independent samples	$0.496 > 0.05$	Accept

the compaction effect between the soil thickness at 50 cm and 30 cm was not significant. The results of compaction times to the reclaimed soil indicate the following: the effect of one-time compaction was not significant. When the compaction was performed three times and more, the compaction effect was more significant than that of the undisturbed original soil. Nevertheless, the difference of the compaction effect between three times compaction and five times compaction was not significant. The porosity of the compacted reclaimed soil had a remarkable difference from

Table 4: Results of multiple comparison analysis.

Comparing subjects	Sample 1-sample 2	Test statistics	Standard error	Standardized test statistics	Significance	Adjusted significance	Result
The impact of soil thickness to the porosity	70 cm-50 cm	−14.778	5.715	−2.586	0.10	0.029 < 0.05	Pass
	70 cm-30 cm	−23.778	5.578	−4.263	0.00	0.000 < 0.05	Pass
	50 cm-30 cm	−9.0	4.497	−2.001	0.45	0.136 > 0.05	Fail
The impact of compaction times to the porosity	5 times-3 times	3.333	5.112	0.652	0.514	1.000 > 0.05	Fail
	5 times-1 time	9.467	5.112	1.852	0.064	0.384 > 0.05	Fail
	5 times-0 times	28.267	8.854	3.192	0.001	0.008 < 0.05	Pass
	3 times-1 time	6.133	5.112	1.200	0.230	1.000 > 0.05	Fail
	3 times-0 times	24.933	8.854	2.816	0.005	0.029 < 0.05	Pass
	1 time-0 times	18.800	8.854	2.213	0.034	0.202 > 0.05	Fail

the uncompacted soil up to three times of compaction. Beyond that, the effect of every additional single compaction was not significant. We ran the Gauss distribution of the porosity values and conducted one-way ANOVA analysis which is widely used in the linear model to further explore the impact of the mutual interactions of the topsoil thickness and times of compaction to the porosity as shown in Table 5 and Figure 5. The results indicated that the interactions between topsoil thickness and times of compaction had significant impacts on the compaction of the reclaimed soil.

3.2.2. Analysis of the Compaction Effect of the Reclaimed Soil with Different Reclamation Methods

(1) The impact of times of compaction on the porosity of the reclaimed soil. According to Figure 6, the porosity values of the 30 cm and 50 cm thick reclaimed soil were gradually reduced with the increasing times of compaction. However, the overall porosity of the 70 cm thick topsoil reached the lowest level after three times of compaction, followed by a turning point from which the porosity started to increase slightly. It can be seen from Figure 7 that the increase of porosity mainly occurred at the 30 cm depth of soil, while the porosity at the 10 cm depth of soil remained decreasing with the increasing times of compaction. This is because the soil at the 10 cm depth had been undergoing longitudinal deformation, leading to the decreased porosity. However, the soil at the 30 cm depth showed extensive lateral deformation due to the coextrusion from the upper and the lower sides.

(2) The impact of the topsoil thickness to the porosity of the reclaimed soil. Figure 6 shows that the porosity increases with the augmented thickness of the topsoil under the same times of compaction, indicating that the thicker the soil layer is, the less impact the compaction has.

(3) The change of the porosity at different depths of sampling to the various reclamation approaches. Figure 8 shows that the porosity at the 10 cm depth is significantly lower than that at the 30 cm depth. This indicates that the mechanical compaction has a significant impact on the porosity of the superficial reclaimed soil with a superior compaction effect. Figure 7 shows that, for both the 50 cm and 70 cm thick of the topsoil, the porosity at 30 cm depth of soil is lower than the one at 10 cm depth of soil under one-time compaction. This indicates that the intermediate soil layer at the 30 cm depth becomes denser with the pressure from the upper and lower sides. When times of compaction gradually increases and reaches to five times, the porosity at the 30 cm depth is equivalent to or even greater than that at the 10 cm depth. The main reason is that the lateral deformation occurred under the increasing pressure in the middle 30 cm depth with increasing times of compaction. In short, the compaction during the reclamation process has higher pressure to the middle soil layer (30 cm) than that at the 10 cm depth, but the compaction effect is largely depended on times of compaction.

3.3. Analysis of the Compaction Effect of the Reclaimed Soil after the One-Year Maintenance Period. Analysis of the soil porosity (Table 2) of the reclaimed soil after the one-year maintenance period is as follows: the skewness is −0.606 with the standard error of 0.536, and the kurtosis is 0.682 with the standard error of 1.038. It indicates that this set of data did not follow the Gauss distribution. The independent sample test in the nonparametric test was utilized to analyze the data. The analytical results showed that the porosity of the reclaimed soil after the one-year maintenance period was not significantly affected by times of compaction, the thickness of the topsoil, and the sampling depth.

Figure 9 shows that, to the uncompacted reclaimed soil, the overall porosity was decreasing as the soil depth increased, indicating that the soil became denser. At the 10 cm depth, the thinner the topsoil was, the larger its porosity was. The reason is that, in the process of irrigation and watering, the thicker soil required more irrigating water, which had greater compaction effect to the surface of the reclaimed soil, resulting in the denser topsoil. At the 30 cm depth, there was no significant difference in the porosity between the three types of reclamation soil thickness. The 30 cm thick soil layer was generally located at the contacting interface of the

Table 5: Tests of between-subject effects.

Source	Type III sum of squares	df	Mean square	F	Significance
Corrected model	27.234#	9	3.026	6.393	0.000
Intercept	0.198	1	0.198	0.419	0.521
Soil thickness ∗ compaction times	27.234	9	3.026	6.393	0.000 < 0.05
Error	17.988	38	0.473		
Total	45.222	48			
Corrected total	45.222	47			

Note. # $R^2 = 0.602$ (adjust $R^2 = 0.508$). Dependent variable: porosity.

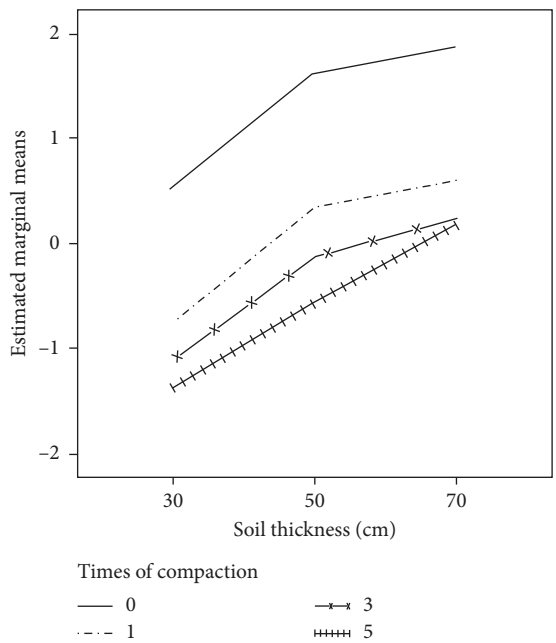

Figure 5: Estimated marginal means of impacts of times of compaction and soil thickness to porosity.

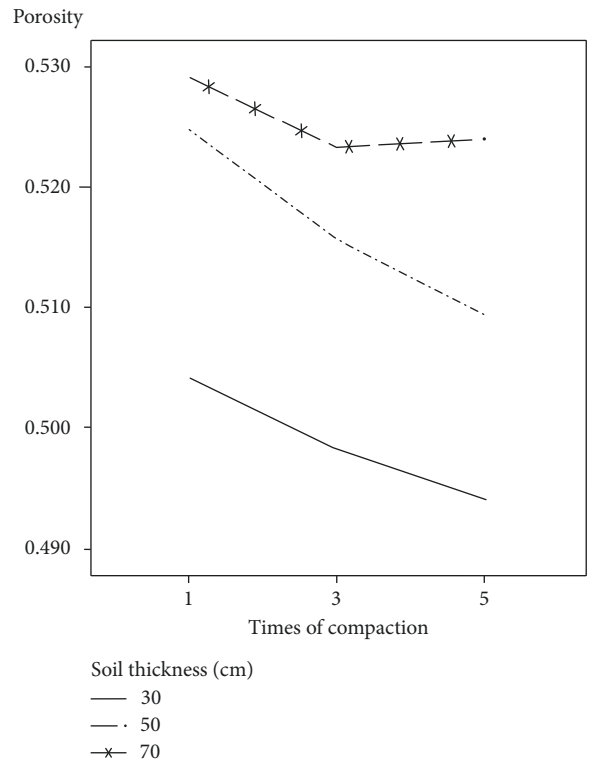

Figure 6: Change of the porosity of different topsoil thickness to times of compaction.

reclaimed soil and waste rocks in which the porosity decreased the most quickly due to the continuous compaction from the long-time accumulation and seepage.

For a reclaimed soil which had been compacted once, the thinner the soil layer was, the smaller the porosity was. The reason is that the compaction effect was better to a thin soil layer. At the 30 cm depth, the porosity generally reached to the maximum level. The reason is that the topsoil became hardening (Figure 10) after compaction due to the irrigation and sunshine exposure, and the porosity at the surface of the soil (at the 10 cm depth) decreased remarkably. The soil below the 30 cm depth became denser due to its own gravity and seepage of water in the soil.

3.4. Comparative Analysis of the Compaction Effect of the Reclaimed Soil before and after the One-Year Maintenance Period. The paired sample test in the nonparametric test was used to analyze the porosity of soil samples uncompacted or one-time compacted at the soil thickness of 10 cm and 30 cm. The analytical results are shown in Table 6. The porosity value (or rank) after the one-year maintenance period was subtracted by the porosity value (or rank) before that period. If it is greater than 0, the positive rank is used, and if it is less than 0, the negative rank is used. In case of 0, it is marked as the tie. In both test methods, the number of negative ranks were 11 and the number of positive rank and tie were 0. The p values calculated by the two test methods were all less than 0.05, indicating that the existing evidence was sufficient to support the rejection of the null hypothesis that the distribution of the porosity was the same before and after the one-year maintenance period. It was thus recognized that there was a significant difference in the porosity before and after the one-year maintenance period.

Figure 11 shows that the overall porosity after the one-year maintenance period is lower than that before the maintenance period, indicating that the one-year maintenance period led to further densification of the soil with irrigating water seepage and soil gravity. For the one-time compacted reclaimed soil, the porosity at the depth of 10 cm before the management and protection period was obviously larger than that after the management and protection period. The reason is that the topsoil was hardening after the maintenance period leading to the reduced porosity. In

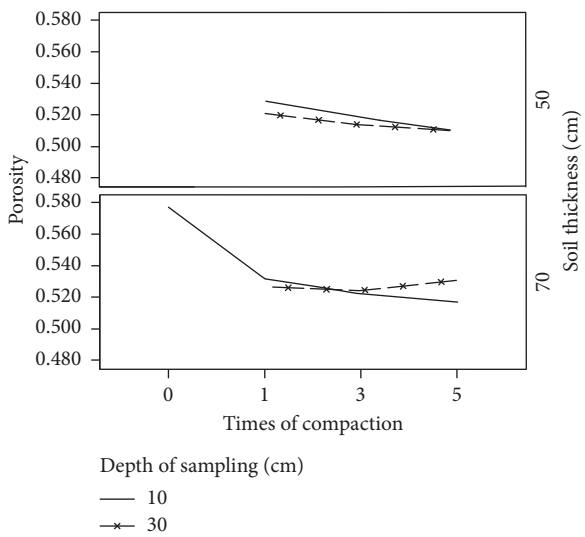

Figure 7: Change of the porosity of different depths of sampling and soil thickness to times of compaction.

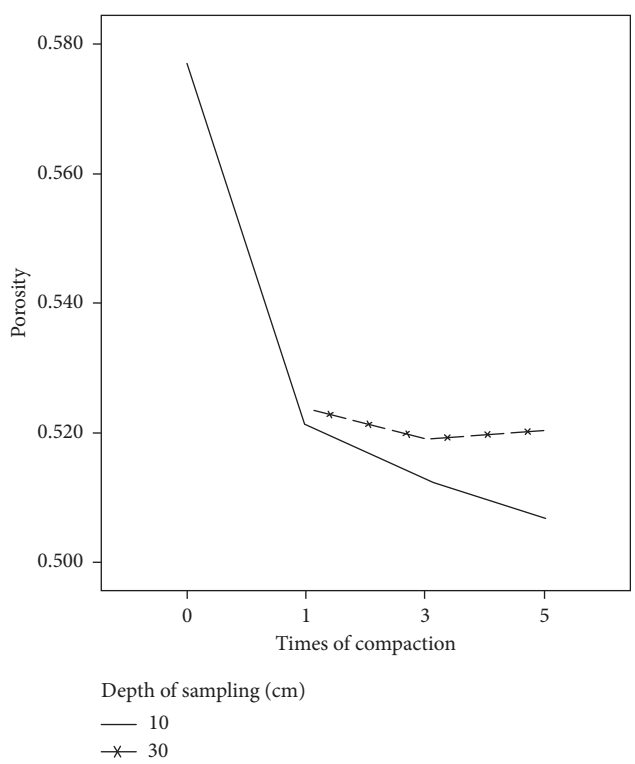

Figure 8: Change of the porosity of different depths of sampling to times of compaction.

contrast, the difference in the porosity at the 30 cm depth was not significant. This suggests that the one-year maintenance period had less compaction effect on the middle layer of the reclaimed soil.

4. Discussion

Compared with the previous analysis of the compaction effect of the reclaimed soil, this analytical study integrated

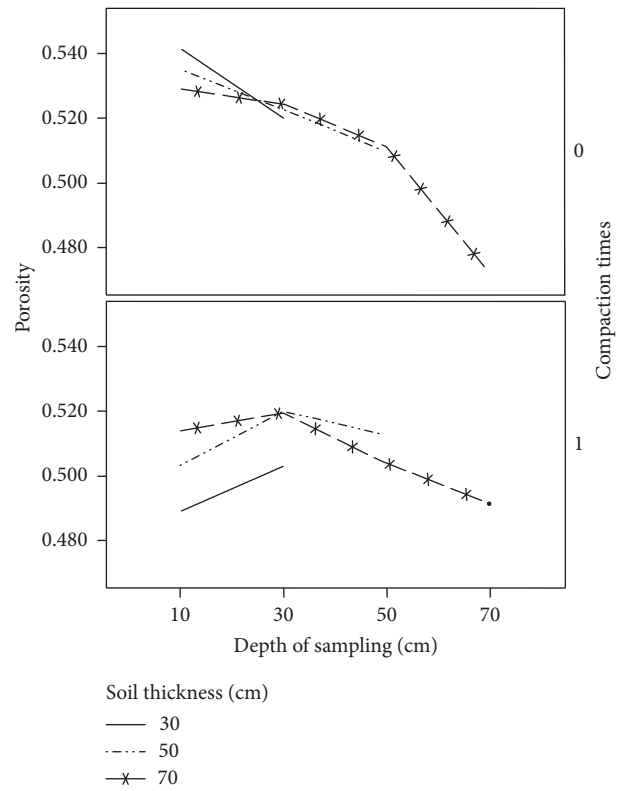

Figure 9: Change of the porosity of different times of compaction and soil thickness to the depth of sampling.

Figure 10: Hardening phenomena of the reclaimed soil with one-time compaction after a one-year maintenance period.

the conditions of reclamation work along with the maintenance period in the nonmetallic mining area of Xinjiang. The plate load experiment method was used to simulate the

Table 6: Analytical results of the paired sample test.

Wilcoxon signed-rank test						Sign test			
Rank	N	Mean rank	Sum of rank	Test statistics	The porosity after MP-the porosity before MP	Rank	N	Test statistics	The porosity after MP-the porosity before MP
Negative ranks	11	6.00	66.00	Z	−2.934	Negative ranks	11	Exact significance (2-sided)	0.001
Positive ranks	0	0	0	Asymptotic significance (2-sided)	0.003	Positive ranks	0		
Tie	0					Tie	0		
Total	11					Total	11		

Note. MP: maintenance period.

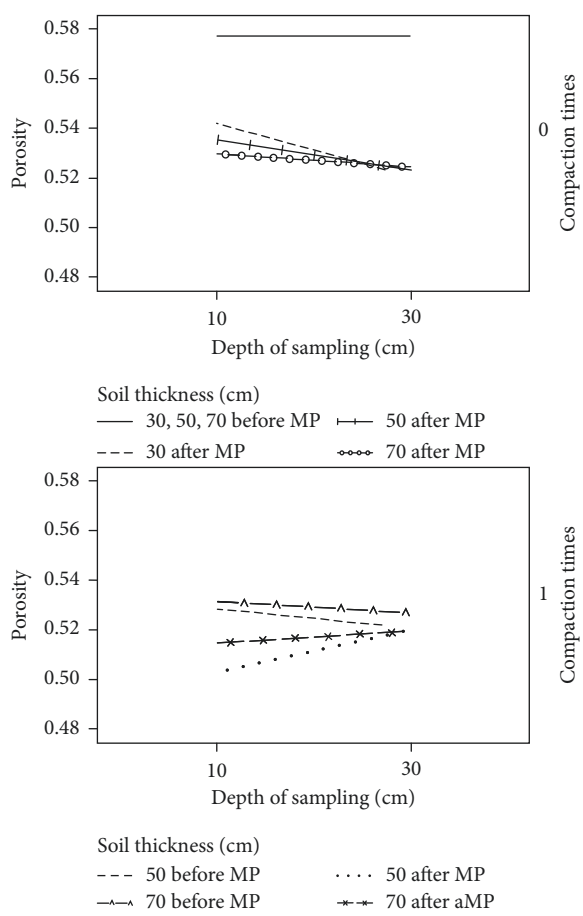

Figure 11: Change of the porosity of a different topsoil thickness to various times of compaction before and after the maintenance period. MP: maintenance period.

compaction effect of reclamation bulldozers on a different topsoil thickness to avoid the dynamic load damage caused by the drop weight test to the reclaimed soil. A direct on-site sampling followed by an indoor experiment strategy was used to analyze the change of the porosity. The experimental results obtained from the simulation was highly consistent with the actual situation.

In this study, the impact factors to the porosity of the reclaimed soil in the nonmetallic mining area of the northern foothills of Tianshan Mountains in Xinjiang was analyzed. On the one hand, the compaction effect of the reclamation machine to the reclaimed soil was analyzed. On the other hand, the change of the porosity of the reclaimed soil before and after the one-year maintenance period was comparatively analyzed, making the entire analysis comprehensive.

Because of the short of test barrels on-site, this study only analyzed the impacts of noncompaction and one-time compaction to the reclaimed soil after the one-year maintenance period, while the impacts of multiple times of compactions to the reclaimed soil were not included, which will be supplemented in the future studies.

According to the analytical results of the compaction effect to the reclaimed soil in the one-year maintenance period, the major factor which has a greater impact on the compaction effect to the reclaimed soil is the migration of water in the unsaturated zone of the reclaimed soil. Studies on the transportation mechanisms of water in the reclaimed soil with a different topsoil thickness and compaction conditions could be conducted in the future.

The pressure monitoring can be performed at different depths of the reclaimed soil to further explore the compaction effect of the reclamation machine to the reclaimed soil.

5. Conclusions

(1) Both the compaction times and the thickness of the reclaimed soil are significant factors affecting the density of the reclaimed soil, and the mutual interaction between the two factors has an impact on the density of the reclaimed soil.

(2) There is a significant difference of the compaction effect to the reclaimed soil between noncompaction and three-time compaction by the reclamation machine. With the increasing times of compaction, the effect of every additional single compaction is weakened.

(3) The thicker the topsoil is, the less effective the compaction effect would be. With the increasing times of compaction, the porosity of the reclaimed soil at the 30 cm and 50 cm thickness gradually decreases. The porosity of the reclaimed soil at 70 cm

thickness was reduced to the lowest level after three times of compaction and then rised slowly.

(4) The reclamation machine shows variable compaction effects at different depths of the reclaimed soil. It has the most significant compaction effect on the superficial part of the reclaimed soil (at the 10 cm depth), at which the porosity is less than the one at the 30 cm depth. The soil layer at the 30 cm depth is located in the middle part of the reclaimed soil and has the highest pressure due to the extrusion from the upper and lower parts. This soil layer could develop lateral deformation after certain compaction times.

(5) There are seepage and capillary transportation of water in the reclaimed soil due to irrigation during the one-year maintenance period. These factors affect the density of the reclaimed soil. For the non-compacted soil, the porosity decreases continuously from shallow to the deep part. For the one-time compacted soil, the porosity decreases drastically due to the topsoil hardening. The porosity at the 10 cm depth is less than the one at the 30 cm depth. Beyond the 30 cm depth, the porosity decreased continuously with the increasing depth.

Data Availability

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

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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