Hindawi
Geofluids
Volume 2022, Article ID 3891030, 12 pages
https://doi.org/10.1155/2022/3891030

Research Article

Experimental Study on Mechanical Strength of Diesel-Contaminated Red Clay Solidified with Lime and Fly Ash

Yu Song[1,2] **Mingzhi Zhang**[1,2] **Xiaohui Gan**[1,2] **Shuaishuai Dong**[1,2] **Song Ding**[1,2] **Yukun Geng**[1,2] **and Jun Li**[3]

[1]*College of Civil and Architecture Engineering, Guilin University of Technology, Guilin 541004, China*
[2]*Guangxi Key Laboratory of Geomechanics and Geotechnical Engineering, Guilin 541004, China*
[3]*Business School of Guilin University of Technology, Guilin 541004, China*

Correspondence should be addressed to Jun Li; 6614083@glut.edu.cn

Received 21 April 2022; Revised 16 May 2022; Accepted 23 May 2022; Published 20 June 2022

Academic Editor: Hao Wu

Diesel-polluted soil is unstable and easy to migrate with environmental changes and causes secondary pollution. In this paper, 0# diesel is used as the pollutant, and lime fly ash is selected as the solidifying material. This paper selects four curing ages of 7D, 14D, 21D, and 28D and four pollution concentrations of 0%, 5%, 10%, and 15%. 20%, 25%, 30%, and 35% four moisture content variables were used to conduct an unconfined compression test, direct shear test, and scanning electron microscope test on diesel-contaminated red clay. The results show that the curing age significantly affects the curing effect, and the curing age of 21D is the optimal age. The mechanical properties of the cured soil were the best at the optimum age and when the pollution concentration was 5%. The mechanical properties of the solidified soil with a moisture content of 30% are the best at the optimal age and the same pollution concentration. Additionally, the scanning electron microscope data indicate that when the pollution concentration increases, the cement created by the interaction of lime, fly ash, and pozzolan increasingly forms. The "oil film" generated by diesel oil seeping into the soil is bound and unable to fill the soil's pores, hence reducing the soil's strength.

1. Introduction

With the growth of China's economy, there are more and more engineering projects. Du et al. [1] pointed out that the annual oil production in China has exceeded 1.8×10^{11} kg, and the oilfield area covers an area of about 3.2×10^5 km^2. Thus, as the industry develops and demand for diesel fuel for vehicle usage increases, diesel fuel consumption and transportation often result in leakage, as shown in the 2013 Beihai diesel tank leaking event in Guangxi and the 2014 Guangxi Nanning diesel tank rollover disaster. A significant quantity of diesel oil seeps into the red clay roadbed and foundation, causing variable degrees of soil pollution. Diesel-contaminated soil is inherently unstable and rapidly migrates in response to environmental changes, resulting in secondary contamination. As a result, efficient soil remediation of diesel contamination is a pressing issue. The remediation methods of diesel-contaminated soil are mainly divided into physical methods (physical separation method, steam extraction method, thermal decomposition, electrolysis, etc.), chemical methods (chemical reduction, chemical leaching, soil performance improvement, and remediation technology, etc.), and biological methods (bioaugmentation method, biological culture method, bacterial injection method, etc.) [2]. Diesel has complex components and various structural properties, which is extremely easy to cause secondary pollution. A single repair method often has an insignificant repair effect and high cost. The research on the restoration of heavy metal ion-contaminated soil has formed a system, but it is still in the exploratory stage to restore oil-contaminated soil and its secondary utilization.

He et al. [3] pointed out that the compressive strength of oily soil treated with lime and fly ash first increased and then decreased with the number of dry-wetting cycles. Shah et al. [4] showed that the geotechnical properties of petroleum-contaminated soil were improved after treating petroleum-contaminated soil with different stabilizers such as lime, fly ash, and cement alone or as admixtures. Stabilizers improve soil geotechnical properties through cation exchange, agglomeration, and pozzolanic action. Adding 10% lime, 5% fly ash, and 5% cement to the contaminated soil works best. Kogbara and Al-Tabbaa [5] mixed one part of slaked lime with four parts of slag, one part of cement, and nine parts of slag cement in diesel-contaminated sandy soil. Theresults show that cement and lime-activated GGBS can effectively reduce theleaching of pollutants in polluted soil. Al-Rawas et al. [6] used cement and cement bypass dust as stabilizers to effectively improve the properties of oil-contaminated soils and provide a safe and effective solution for practical construction applications. Portelinha et al. [7] pointed out that diesel pollution affects soil water holding capacity and unsaturated hydraulic conductivity, forming a curved shape similar to clay materials. Bian et al. [8] evaluated the shear characteristics of oil-contaminated soil by resistivity and pointed out that under constant compaction and saturation, the shear strength of oil-contaminated soil decreased with the increase in resistivity.

Zhou et al. [9] used a direct shear test, variable head penetration test, and compression test to point out that with the increase in diesel content, the cohesion of oily soil first increased and then decreased, and the internal friction angle first changed slightly and then increased. The compressibility and permeability of oil-contaminated soil first decreased and then increased with the increase in diesel content. Zheng et al. [10] found through the unconfined compressive strength test that it decreases with the increase in oil content, but when the water content is low, the soil strength increases instead; Chen et al. [11] found through the indoor quick shear test that the bonding force between sand particles is small, the influence of nondielectric oil on the bonding force between soil particles is much smaller than that of water, and the effect of crude oil and diesel oil on the shear strength of unsaturated sand is not significant; Li [12] pointed out that the permeability coefficient of diesel-contaminated loam is about 97% lower than that of clean loam when the oil content is 8%; He et al. [13] simulated the dry-wet cycle indoors and confirmed the immobilization of oil-contaminated soil by lime fly ash with the help of an unconfined compression test. It has high compressive strength; Zha et al. [14] and other studies pointed out that the use of fly ash and a small amount of lime mixture can effectively improve the engineering properties of expansive soil, reduce the expansion and shrinkage of expansive soil, and improve the strength of expansive soil. Li et al. [15] have confirmed that lime fly ash can effectively improve the mechanical properties of oil-contaminated saline soil. Han et al. [16] point out that under a CNS boundary condition, the shear stress for single-joint and double-joint specimens increases slowly with the increase in shear displacement. Song et al. [17] propose that calcium oxide enhances the strength of Zn^{2+}-contaminated soil because calcium oxide will react with SiO_2, Al_2O_3, and Fe_2O_3 in the red clay to produce C-S C-A-H. Song et al. [18] compared the red clay before and after pollution; it is found that under the same axial strain, the damage variable increases with the increase in confining pressure. Song et al. [19] pointed out that with the increase in the number of wetting and drying cycles, the soil particles' connection is closed, the soil porosity decreases, and the strength increases.

In environmental and geotechnical engineering, the solidification treatment of diesel-contaminated red clay is a study area that cannot be overlooked. Therefore, in this paper, Guilin red clay is used as the test material, lime with a strong curing effect and fly ash with strong adsorption are selected, and through the unconfined compression test, direct shear test, and scanning electron microscope test, the effect of different pollution concentrations, different mechanical properties, and microstructure of cosolidified diesel-contaminated red clay with water content and different curing ages was investigated.

2. Experimental Material and Test Methods

2.1. Experimental Materials

2.1.1. Diesel. The pollutant used in this test is $0^{\#}$ diesel, taken from the Sinopec gas station in Guilin City. The color of the $0^{\#}$ diesel is light yellow with light green luster, slightly soluble in water, with good fluidity but greater viscosity than water and substantial volatility; it has a special pungent odor. The relative density of the diesel used is 0.857. The viscosity coefficient is 3.56-4.05 mPa·s, and the freezing point is -25.82°C.

2.1.2. Red Clay. The soil used in the test was taken from a foundation pit in Lingui District, Guilin City, which belongs to the subregion of Guofeng Plain in the structural erosion landform area, with many low mountains and hills. The soil layer structure can generally be divided into three layers. The first layer is plain fill (Q_4^{ml}), mainly composed of cohesive soil, crushed stone, and schist, with a loose structure. The layer thickness is 0.40-2.00 m, and the average thickness is 1.01 m. The second layer is plastic secondary red clay (Q_3^{al+pl}), which is uniform in soil quality, smooth in section, and slightly glossy. The layer thickness is 0.20-5.70 m, and the average thickness is 1.65 m. The third layer is pebble gravel soil (Q_3^{al+pl}), mainly gray-brown pebble gravel, the layer thickness is 0.50-2.50 m, and the average thickness is 0.85 m. The red clay used in this experiment was taken from the second layer at a depth of 3-5 m. The red clay was retrieved, air-dried, crushed, passed through a 2 mm sieve, stored in a moisture-proof plastic bucket, sealed for use, and subjected to geotechnical tests. The properties of its basic physical properties and parameters are shown in Table 1.

2.1.3. Fly Ash. The fly ash was purchased from Gongyi Longze Water Purification Material Co., Ltd. It is mainly composed of coal ash and slag, with strong adsorption properties, the specific gravity is between 1.95 and 2.36, and the dry density is 450 kg/m^3 to 700 kg/m^3. The specific surface area is between 220 kg/m^3 and 588 kg/m^3, and the main components are SiO_2, Al_2O_3, and Fe_2O_3. Fly ash can undergo recrystallization, ion adsorption and exchange, carbonation, and pozzolanic reaction with lime, forming a "reticular" and "rod-like" structure in the soil, which

Table 1: Physical properties of red clay.

Optimal moisture content (%)	Maximum dry density (g/cm^3)	Proportion (G_S)	Compression modulus (MPa)	Liquid limit (%)	Plastic limit (%)	Plasticity index (I_P)
30.00	1.515	2.73	10.15	57.95	31.22	26.73

significantly improves the mechanical properties of the solidified soil.

2.1.4. Lime. Lime is a common solidified material purchased from Xilong Science Co., Ltd. as bottled quicklime, with white or gray lumps, granules, or powder. The calcium oxide content is greater than or equal to 98%. CaO reacts with water to form $Ca(OH)_2$, of which OH^- can decompose Si-O and Al-O bonds in the glass body of fly ash, which can fully stimulate the activity of fly ash. At the same time, it provides Ca^{2+} for the formation of hydraulic gels in the hydration reaction.

2.2. Test Method. The naturally air-dried red clay was crushed and passed through a 2 mm sieve. Calculate the mass of air-dried soil, water, diesel oil, and lime fly ash required to prepare the soil sample (diesel and solidified material are mixed according to the mass percentage of the dry soil). The procedure for the test is shown below.

The first step is to equally distribute the weighted diesel oil into the soil, cover it with plastic wrap, and allow it to sit for 12 hours so that the oil molecules may infiltrate the soil particles. The air-dried soil preparation sample is sprayed with distilled water in the second stage. In the third step, the contaminated soil and curing agent were combined and stirred equally and sealed for 24 hours in the third phase, according to the prescribed dose of the curing agent. During this time, the soil samples were flipped over often to ensure that all of the components were well mixed. According to the "Geotechnical Test Method Standards" (GB/T50123-2019) [20], a standard vertebral triaxial sample with a diameter of 39.1 mm and a height of 80 mm and a reshaped ring knife sample with a diameter of 61.8 mm and a height of 20 mm were prepared by the static pressure method for unconfined compressive strength and direct shear tests. The unconfined compressive strength test and direct shear test were carried out after curing for 7D, 14D, 21D, and 28D under standard curing conditions (curing temperature is 20 ± 2°C, humidity $\geq 95\%$); dry density of the sample is 1.40 g/cm^3.

Since diesel oil is a nonaqueous liquid, it will not dissolve with the pore water in the soil after infiltrating it, forming a "diesel pore liquid." Therefore, fly ash with strong adsorption and alkalinity is selected, which can strongly combine with oily substances through intermolecular attraction and chemical chain, and is irreversible. Lime is a common solidified material for treating polluted soil, and lime-solidified soil has high shear strength and compressive strength. The combination of lime and fly ash is used to solidify diesel-polluted soil. The two have a pozzolanic reaction and solidification reaction, forming a cementitious compound to fill in the soil particles, which has a good solidification effect and improves the soil's mechanical strength. After many attempts, the moisture content was set to 20%, 25%, 30%, and 35%. The oil content was set to 0%, 5%, 10%, and 15%. The curing age is set as 7D, 14D, 21D, and 28D. The curing material is 20% fly ash+12% lime.

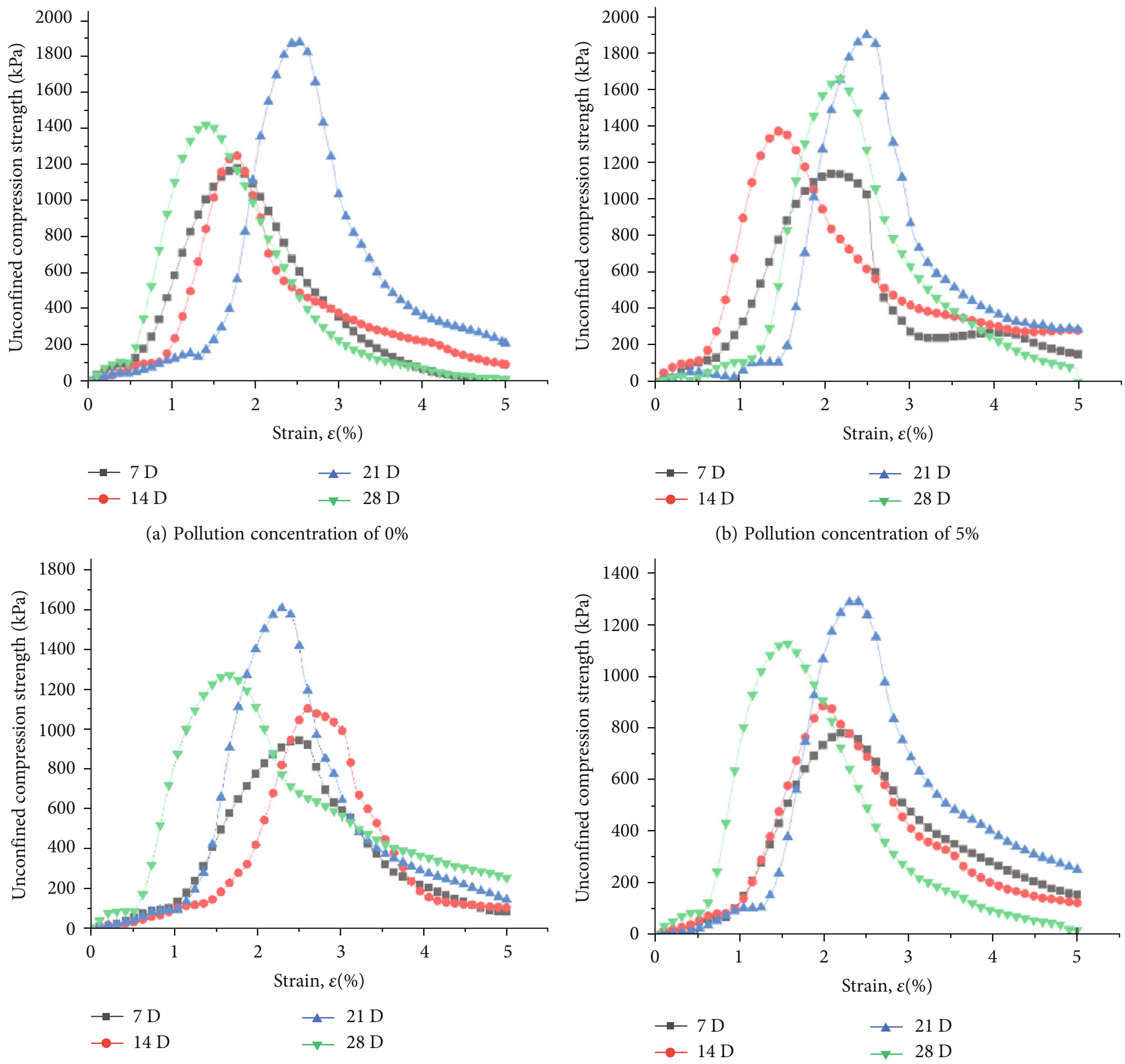
3. Characteristics of Unconfined Compressive Strength of Cured Diesel-Contaminated Red Clay

3.1. Influence of Curing Age on the Unconfined Compression Strength of Cured Diesel-Contaminated Soil. The unconfined compressive strength is a critical evaluation index of the curing/stabilization technology treatment effect [20, 21]. According to the geotechnical test method standard, the maximum axial stress is taken as the unconfined compressive strength without side limitation. If the maximum axial stress is not apparent, the corresponding stress of the axial strain of 15% is taken as the unconfined compressive strength. From Table 1, it can be seen that the optimal moisture content of the soil used in this test is 30%. Therefore, the unconfined compression strength selected the moisture content of 30% and the pollution concentration of 0%, 5%, 10%, and 15% and explored the unconfined compression strength of the same-dosage curing agent at the curing age of 7D, 14D, 21D, and 28D. The unconfined compression strength of different curing ages obtained by the test is shown in Figure 1.

It can be seen from Figure 1 that the unconfined compressive strength of lime-fly ash-solidified diesel-polluted soil increases first and then decreases with the increase in curing age, and the strength reaches its peak when the curing age is 21D. Compared with the unconfined compressive strength with a curing age of 7D and a pollution concentration of 10%, the unconfined compressive strength increased by 159%, 166%, 134%, and 144%, respectively.

With the increase in age, the failure strain corresponding to the ultimate strength of the solidified diesel-contaminated red clay increased first and then decreased (2.48%, 2.61%, 2.31%, and 1.64%, respectively). Analysis of the reasons shows that the pozzolanic reaction between lime and fly ash has fully occurred, and this reaction is a slow-developing and time-consuming process.

With the increase in curing age, the active silica in fly ash and the Ca^{2+} ionized from lime forms C-S-C and C-A-H and condenses on the surface of soil particles, increasing the effective contact area between soil particles, thereby improving soil strength. At the same time, after the $Ca(OH)_2$ lime hydration, the SiO_2 forms sol, and Al_2O_3 on the surface of the fly ash glass body dissolves slowly and gradually reacts with $Ca(OH)_2$ to form calcium silicate, and calcium aluminosilicate and other compounds are filled in the soil The



(a) Pollution concentration of 0%

(b) Pollution concentration of 5%

(c) Pollution concentration of 10%

(d) Pollution concentration of 15%

FIGURE 1: Stress-strain curve of cured diesel-contaminated red clay at different curing ages.

connection strength between the particles and the soil particles is enhanced. The unconfined compressive strength of the solidified soil is improved.

3.2. Influence of Pollution Concentration on the Unlimited Compressive Strength of Cured Diesel-Contaminated Soil. To explore the influence of diesel pollution concentration on the unconditioned compressive strength of cured soil, the unconfined compressive strength of cured soil under the optimal conditions of 21D curing age and moisture content of 30% was selected to explore the unconventional compressive strength of cured soil under different diesel pollution concentrations. The unconstrained compressive strength of the diesel fuel under different concentrations obtained by the test is shown in Figure 2.

It can be seen from Figure 2 that as the pollution concentration increased from 5% to 15%, the unconventional compressive strength of the cured soil decreased with the increase in the pollution concentration, decreasing by 15.5% and 19.4%, respectively. The stress-strain curve of the cured soil under different concentrations is mainly divided into four stages: the elastic stage—the stress-strain curve of this section is linear, and the cured soil sample is inelastic deformation; the yield stage—the stress-strain curve of this section is close to a straight line, and the solidified soil sample begins to undergo plastic deformation; the strengthening stage—the stress of this section slowly increases until the peak, and the solidified soil sample will be destroyed; and the failure stage—the stress-strain curve of this section shows a downward trend until the cured soil sample is destroyed.

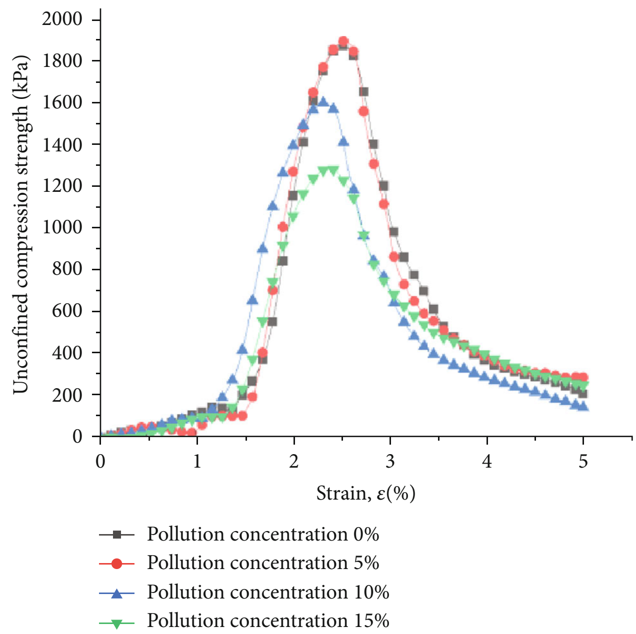


Figure 2: Stress-strain curve of cured diesel-contaminated red clay at different pollution concentrations.

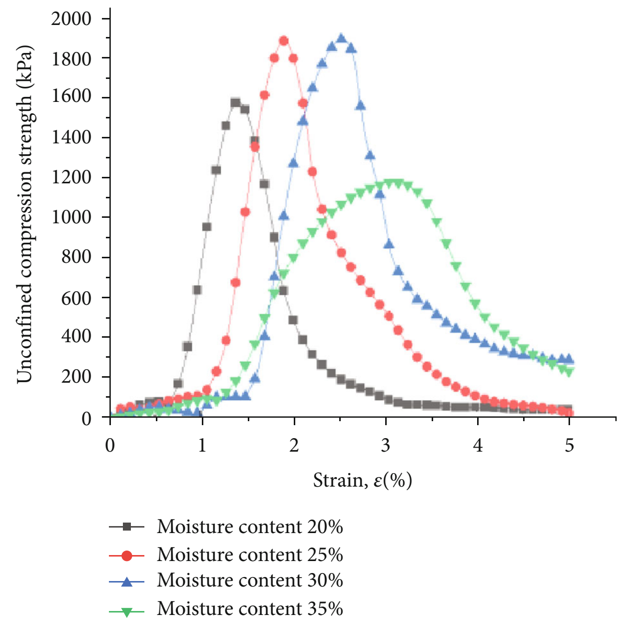


Figure 3: Stress-strain curve of cured diesel-contaminated red clay at different moisture content.

The main reason is that after the diesel molecules penetrate the soil, a layer of "-film" will be formed on the surface of the soil oil as the pollution concentration increases, and the "oil-film" gradually increases and thickens. Because diesel is hydrophobic, the "oil-film" will hinder the infiltration of water, resulting in gelatinous particles generated by the reaction of the cured material unable to fill the soil particles, so that the unconfined compressive strength decreases with the increase in pollution concentration.

3.3. Influence of Moisture Content on the Unlimited Compressive Strength of Cured Diesel-Polluted Soil. To explore the influence of moisture content on the unconfined compressive strength of cured soil, the unconditioned compressive strength of cured soil under different moisture content was selected with a curing age of 21D, a pollution concentration of 5%, and a moisture content of 20%, 25%, 30%, and 35%. The unconstrained compressive strength under different diesel pollution concentrations obtained by the test is shown in Figure 3.

It can be seen from Figure 3 that the unconfined compressive strength of the solidified soil increases and then decreases with the increase in water content, and with the increase in moisture content, the destructive strain of the cured soil shows a gradual increase trend, and the failure strain of 20%, 25%, 30%, and 35% is 1.38%, 1.88%, 2.47%, and 3.07%, respectively. The primary explanation for this might be that when moisture content rises, the percentage of water molecules and oil molecules in the soil increases, whereas the fraction of water molecules and cementitious gels formed by cured materials increases.

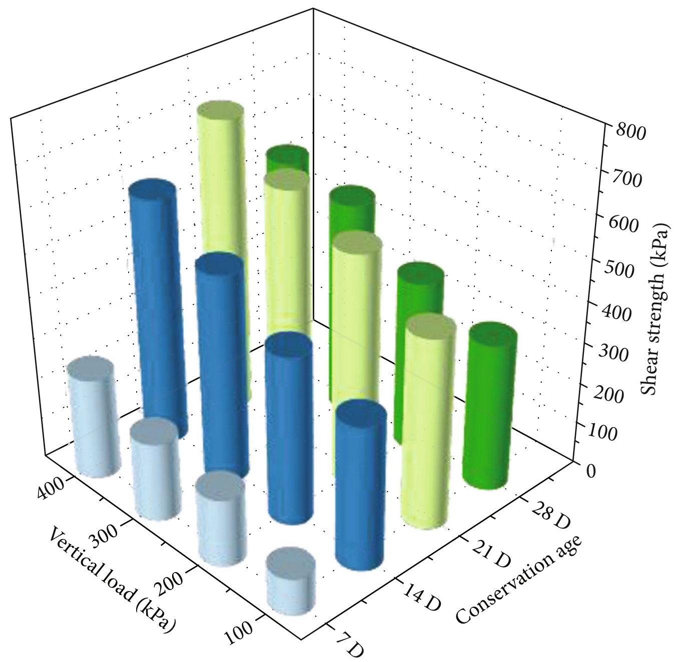
Most of the components in the pores of the cured soil are water molecules, which reduce the curing effect, so the compressive strength of the soil is reduced. At the same time, the diesel infiltration into the soil will produce a cohesive effect on the soil particles. Because the quantity of water molecules between soil particles increasingly exceeds the number of oil molecules, the bonding effect steadily diminishes. The unconfined compressive strength of the cured soil decreases with the increase in moisture content.

4. Shear Strength Characteristics of Solidified Diesel-Polluted Soil

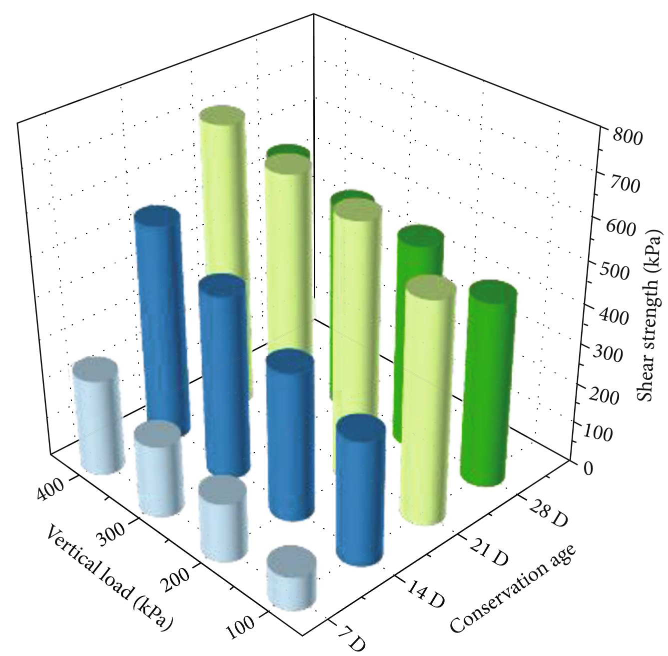
4.1. Effect of Curing Age on the Shear Strength of Cured Diesel-Polluted Soil. A straight shear test shows that the shear strength of cured diesel-contaminated red clay under different curing ages is obtained by a straight shear test, as shown in Figure 4.

It can be seen from Figure 4 and Table 2 that under the condition of the same pollution concentration, with the increase in the curing age, the shear strength of the cured soil under the same vertical load is gradually increased compared with that of the cured soil with a curing age of 7D and a pollution concentration of 10%, the vertical load is 100 kPa, and the shear strength is increased by 318%; the vertical load is 200 kPa, and the shear strength is increased by 228%; the vertical load is 300 kPa, and the shear strength is increased by 190%; the vertical load is 400 kPa, and the shear strength is increased by 173% at the vertical load of 400 kPa.

Compared with the cured soil with a curing age of 7D and a pollution concentration of 10%, the cohesion of cured soil is increased by 507%, and the internal friction angle is increased by 54%. Several factors contributed to this, including low vertical loads and short curing ages. Lime hydration reaction-produced $Ca(OH)_2$ could not ultimately promote

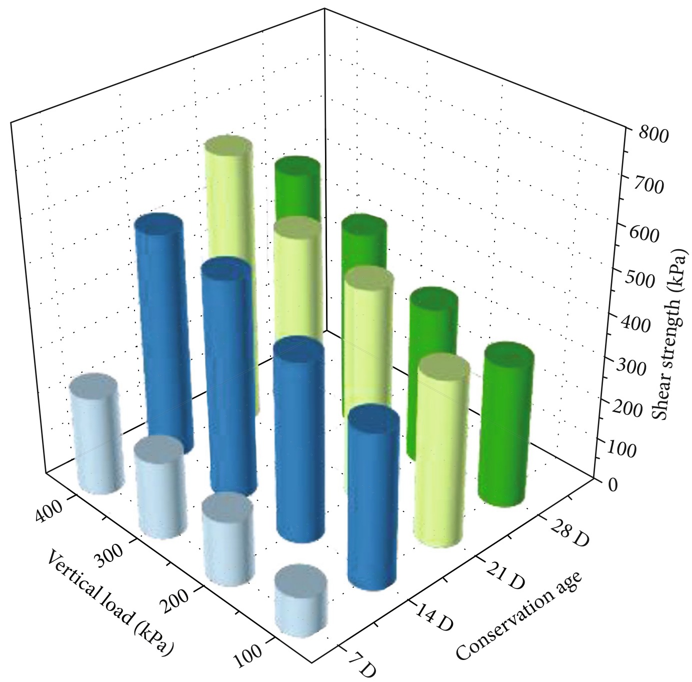


(a) Pollution concentration of 0%

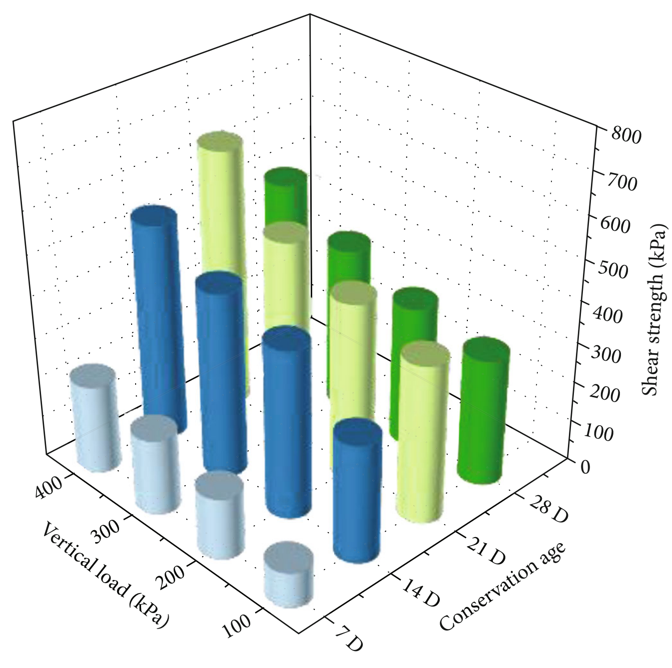


(b) Pollution concentration of 5%

Figure 4: Continued.



(c) Pollution concentration of 10%



(d) Pollution concentration of 15%

Figure 4: Shear strength and parameters of cured diesel-contaminated red clay under different curing ages.

fly ash activity, and calcium silicate and other gels created by volcanic-ash interaction were less active. Some of the products are blocked by the "oil-film" formed on the soil's surface by diesel infiltration into the soil and cannot be filled into the soil particles, and there are pores between the soil particles. The shear strength of the soil is reduced.

With the increase in the curing age, the curing reaction is sufficient, and a large number of gels such as calcium silicate are generated, covering the "oil-film." When the vertical load increases, the product will be pressed into the "oil-film" to fill the soil particles, so that the pores between the soil particles become less, thereby improving the shear strength of the cured soil.

4.2. Influence of Pollution Concentration on the Shear Strength of Cured Diesel-Contaminated Soil. The shear test of the cured soil sample with a curing age of 21D was selected to obtain the shear strength of cured diesel-contaminated red clay under different pollution concentrations, as shown in Figure 5.

Table 2: Cohesion and internal friction angle of solidified soil under different curing ages and pollution concentrations.

Pollution concentration		Curing age 7D	14D	21D	28D
0%	c	47.678	249.738	382.776	291.75
	φ	26.5	40.4	39.4	33.6
5%	c	35.7585	220.174	508.812	431.012
	φ	26.7	37.9	27.0	16.3
10%	c	53.061	309.644	322.87	258.296
	φ	24.3	30.5	37.5	33.8
15%	c	51.9075	231.844	287.86	241.958
	φ	23.5	37.4	39.2	30.3

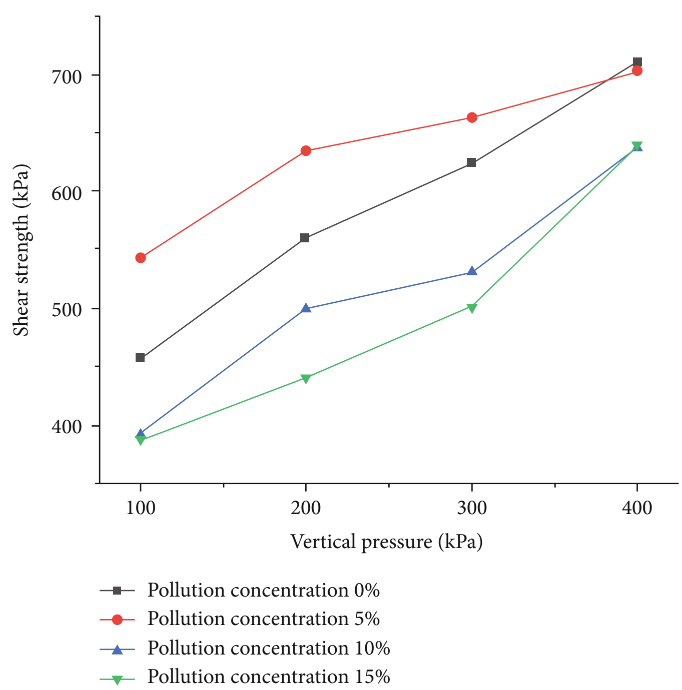


Figure 5: Effects of different pollution concentrations on shear strength of cured diesel-contaminated red clay.

It can be seen from Figure 5 that at the same curing age and the same moisture content, the shear strength of the contaminated soil with a combined curing diesel pollution concentration of 5% of the lime fly ash has the best shear resistance compared with that of the cured soil with a pollution concentration of 15%; the shear strength increases by 40% at the vertical load of 100 kPa; the shear strength increases by 44% under the vertical load of 200 kPa; the shear strength increases by 32% under the vertical load of 300 kPa; and the shear strength increases by 9% at the vertical load of 400 kPa. Compared with the cured soil cohesion of 10% at the same curing age, the cohesion of the cured soil decreased by 34%, and the internal friction angle decreased by 2.5%.

On the other hand, the contamination concentration was negatively correlated with the curing effect. After diesel infiltration into the soil, analysis of the reasons will be covered with a layer of "oil-film" on the surface of the soil. When the pollution concentration is low, the "oil-film" cannot be covered entirely on the soil. The "oil-film" adsorbed by the curing reaction is less generated by the gel condensation; most of the products fill into the pores between the soil particles; with the increase in pollution concentration, the "oil-film" coverage area increases; most of the products are adsorbed and cannot be filled into the soil particles to provide strength for the solidified soil. Therefore, as the pollution concentration increases, the shear strength of the cured soil decreases.

4.3. Effect of Moisture Content on Shear Strength of Solidified Diesel-Polluted Soil. The shear test of the cured soil sample with a curing age of 21D was selected to obtain the shear strength of cured diesel-contaminated red clay at different moisture content rates.

It can be seen from Figure 6 that under the same curing age and the same pollution concentration, the shear resistance of contaminated soil with a combined curing diesel

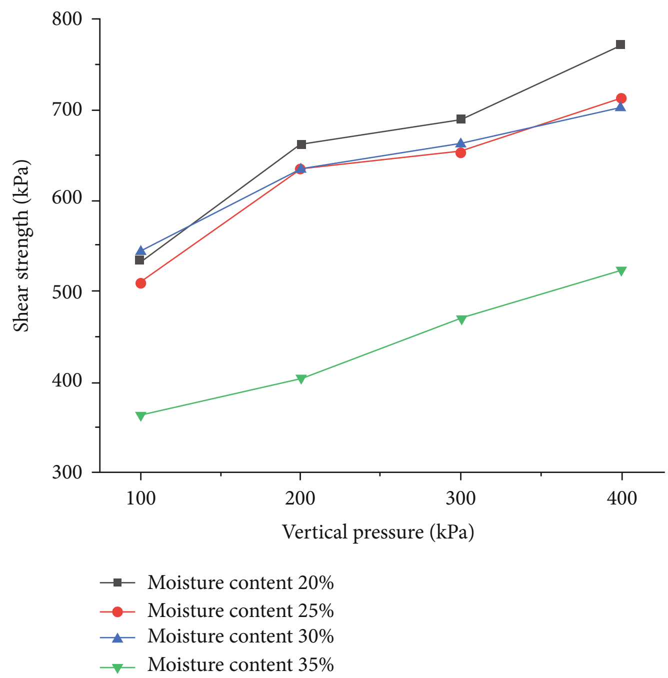


Figure 6: Effect of different moisture content on shear strength of cured diesel-contaminated red clay.

moisture content of 20% is the best. Compared with contaminated soil with a moisture content of 35% under the same conditions, the shear strength increased by 32% under the vertical load of 100 kPa, the shear strength increased by 39% at the vertical load of 200 kPa, the shear strength increased by 31.8% under the vertical load of 300 kPa, and the shear strength increased by 32.2% under the vertical load of 400 kPa. Compared with the cured soil with a moisture content of 35% at the same curing age, the cohesion of cured soil decreased by 36%, and the internal friction angle decreased by 24%.

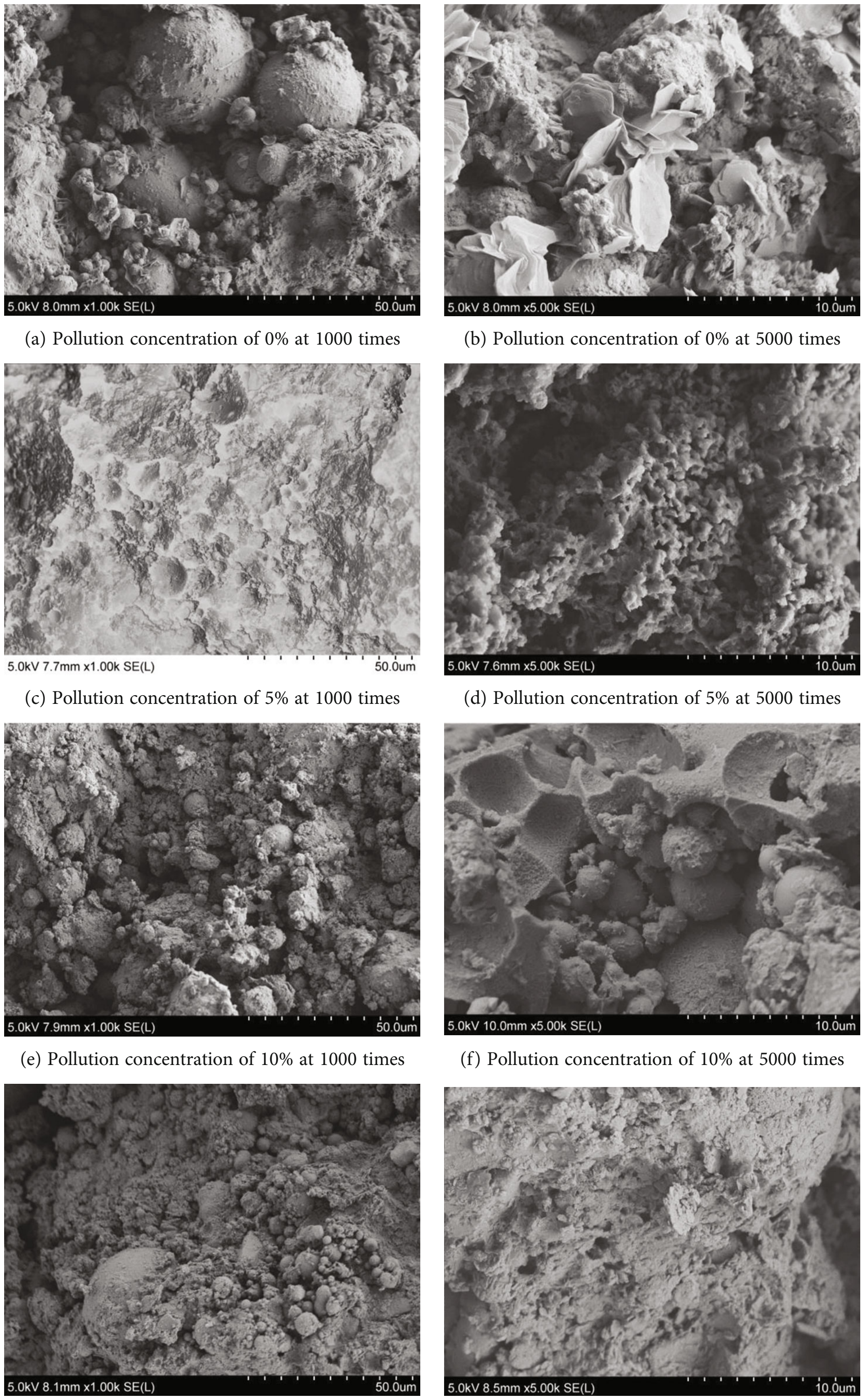
Furthermore, the moisture content is negatively correlated with the curing effect. Analyze the reasons; when the moisture content is low, the soil particles are filled with glue gel generated by water molecules and curing reaction, the moisture in the soil can provide strength, and the shear strength of the cured soil is provided by the combination of water molecules and the cement condensate generated by the curing reaction; with the increase in moisture content, the water in the soil is excessive, not providing strength; the shear strength of the cured soil is mainly provided by the gel condensate generated by the curing reaction, and the pore water mainly plays a lubricating role. Therefore, the shear strength of cured soil at low moisture content is higher than that of cured soil at high moisture content. At the same time, the higher moisture content will reduce the adsorption of the cement, resulting in the cohesion of the cured soil decreasing with the increase in the moisture content.

5. Influence of Pollution Concentration on the Microscopic Characteristics of Solidified Diesel-Polluted Soil

A healed soil sample with optimum curing age of 21D and moisture content of 30% was chosen for scanning electron microscopy tests based on comparisons of the microscopic properties under various pollution levels. The scanning electron microscopy (SEM) test uses Hitachi Corporation's S-4800 field emission scanning electron microscope. To obtain more explicit microscopic morphology, the central part of the soil sample is gold-injected to increase electrical conductivity. Figure 7 shows the microscopic morphology of cured soils at different concentrations at 1000 times and 5000 times magnification.

Comparing the microscopic morphological photos of lime fly ash combined with curing contaminated diesel soil under different pollution concentrations, when the pollution concentration is 0%, the curing reaction generates a large number of filamentous, needle-like, and flake gel crystals. With the adsorption effect of fly ash, the fly ash is closely connected with soil particles, mainly through point-to-point or point-to-surface connections. Some of the products are stacked on top of the soil particles in flakes, and the number of loose and tiny soil particles in the soil body is small. When the pollution concentration is 5%, the diesel molecules penetrate the soil, the fly ash adsorbs the diesel into the soil particles, the arrangement is uneven, there are still more pores, and the gel crystals generated by multiple curing reactions form a smaller-scale mesh unit structure (see Figure 7(d)), which improves the strength of the cured soil.

When the pollution concentration reaches 10%, the number of oil molecules rises, and the gel crystal forms a bigger size agglomeration that is more consistently structured but still has huge holes. More granular debris is adsorbed by diesel to the surface of the soil particles, and a large number of diesel molecules form a honeycomb structure and bond with the agglomerate. When the pollution concentration is 15%, large-scale agglomerates form aggregates, and the aggregates are primarily in contact with



(a) Pollution concentration of 0% at 1000 times

(b) Pollution concentration of 0% at 5000 times

(c) Pollution concentration of 5% at 1000 times

(d) Pollution concentration of 5% at 5000 times

(e) Pollution concentration of 10% at 1000 times

(f) Pollution concentration of 10% at 5000 times

(g) Pollution concentration of 15% at 1000 times

(h) Pollution concentration of 15% at 5000 times

Figure 7: Microscopic morphology of solidified soil under different pollution concentrations.

surfaces, with fewer pores and larger particles. The increase in pollution concentration increases the thickness of the “oil-film” formed by diesel infiltration into the soil, and the adhesion to large particle aggregates is more substantial so that the cured products cannot be filled into the soil particles and the soil strength cannot be improved. The microscopic morphology of the cured soil under different pollution concentrations is consistent with the macroscopic unconfined compressive strength characteristics and shear strength characteristics of the cured soil under different pollution concentrations.

6. Conclusion

This paper is aimed at solving the problem of diesel pollution red clay under different influencing factors and uses lime fly ash as a curing agent. Based on the indoor geotechnical tests, conclusions can be drawn as follows:

(1) The diesel-contaminated red clay cured with lime and fly ash has higher compressive strength and shear strength. When the content of the curing agent is certain, the curing age of 21D is the optimal age. Compared with the curing age of 7D, the unconfined compression strength of the same moisture content and the same pollution concentration increases by 159%, 166%, 134%, and 144%, respectively. Compared with the vertical loads of 100 kPa, 200 kPa, 300 kPa, and 400 kPa under the same moisture content and pollution concentration during the 7D curing period, the shear strength increases by 40%, 44%, 32%, and 9%, respectively

(2) The failure mode of solidified diesel-contaminated soil is strain softening. When the pollution concentration increased from 5% to 15%, the unconfined compressive strength of solidified soil decreased with the increase in pollution concentration, which decreased by 15.5% and 19.4%, respectively. As the pollution concentration increases, the viscosity of diesel oil slows down the rate of ash reflection. On the other hand, the "oil-film" formed by the infiltration of diesel oil into the soil particles gradually thickens, which hinders the filling of the gels generated by the curing reaction into the soil. Therefore, the mechanical strength of contaminated soil cannot be improved

(3) The main reason for improving the strength of the solidified contaminated soil is that the cement particles formed by the reaction of multiple fly ash and lime pozzolans are connected to form a network structure filled into the soil particles, and the particles are closely arranged to form tight connections. As the pollution concentration increases, the diesel-bonded cement particles cannot enter the soil particles, and the soil strength decreases. The consistency of the microstructural characteristics and the change of the macroscopic mechanical strength of the solidified diesel-polluted soil were confirmed

Data Availability

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

Conflicts of Interest

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

Acknowledgments

This research was funded by the National Key Research and Development Projects of China (Grant No. 2019YFC507502), National Natural Science Foundation of China (Grant No. 41967037), and Guangxi Science and Technology Plan Project (Grant No. RZ2100000161).

References

[1] W.-D. Du, Y.-Y. Wan, N.-N. Zhong, J.-J. Fei, and Z.-H. Zhang, "Current status of oil pollution from soil and sediments," *Journal of Wuhan University (Science Edition)*, vol. 57, no. 4, pp. 311–322, 2011.

[2] Q. Yang, M.-l. Wu, M.-Q. Nie, T.-T. Wang, and M.-H. Zhang, "Bioremediation technology and microbial ecological effects of oil-contaminated soil," *Environmental Science*, vol. 36, no. 5, pp. 1856–1863, 2015.

[3] Z.-j. He, C. Shou-xi, and L. Min, "Effect of wetting and drying cycles on the compressive strength of oil-contaminated soil treated with lime and fly ash," *Journal of Engineering Geology*, vol. 26, no. 2, pp. 438–444, 2018.

[4] S. J. Shah, A. V. Shroff, J. V. Patel, K. C. Tiwari, and D. Ramakrishnan, "Stabilization of fuel oil contaminated soil-a case study," *Geotechnical & Geological Engineering*, vol. 21, no. 4, pp. 415–427, 2003.

[5] R. B. Kogbara and A. Al-Tabbaa, "Mechanical and leaching behaviour of slag-cement and lime-activated slag stabilised/solidified contaminated soil," *Science of the Total Environment*, vol. 409, no. 11, pp. 2325–2335, 2011.

[6] A. Al-Rawas, H. F. Hassan, R. Taha, A. Hago, B. Al-Shandoudi, and Y. Al-Suleimani, "Stabilization of oil-contaminated soils using cement and cement bypass dust," *Management of Environmental Quality: An International Journal*, vol. 16, no. 6, pp. 670–680, 2005.

[7] F. H. Portelinha, N. De Souza Correia, I. Santos Mendes, and J. W. Silva, "Geotechnical properties and microstructure of a diesel contaminated lateritic soil treated with lime," *Soil and Sediment Contamination: An International Journal*, vol. 30, no. 7, pp. 838–861, 2021.

[8] H. Bian, S. Liu, Y. Chu, and G. Cai, "Estimation of oil-contaminated soils mechanical characteristics using electrical resistivity," *The International Congress on Environmental Geotechnics*, 2018, pp. 645–652, Springer, Singapore, 2018.

[9] Z. Xing, C. Yi, and S. Ming-nan, *Experimental study on the effect of diesel pollution on the engineering properties of silty clay in Shanghai*, vol. 43, no. 3, 2015.

[10] Z. Tianyuan, Y. Junjie, L. Yongxia, and L. Jiangjiao, "Experimental study on engineering properties of diesel contaminated soil," *Engineering Investigation*, vol. 41, no. 1, pp. 1–4, 2013.

[11] C. Wei-sheng, T. Ling, and X.-l. Zheng, "Study on shear strength of oil-polluted sand soil," *Engineering survey*, vol. 41, no. 1, pp. 1–4, 2013.

[12] L. Mei, *Study on the Residues of Petroleum in Aquifers and Their Hydrological Properties*, Ocean University of China, 2008.

[13] Z.-J. He, C. Shou-xi, and L. Min, “Effect of the dry and wet cycle on compressive strength of lime fly ash cured petroleum-contaminated soil,” *Journal of Engineering Geology of Cheng Survey*, vol. 26, no. 2, pp. 438–444, 2018.

[14] Z. Fu-Sheng, L. Song-yu, and D. Yan-jun, “Lime-fly ash modified expansive soil test,” *Journal of Southeast University (Natural Science Edition)*, vol. 43, no. 2, pp. 339–344, 2007.

[15] M. Li, C. Wang, H.-P. Du, and J.-X. Zhang, “Mechanical properties of lime fly ash combined with solidifying petroleum pollution coastal saline soil,” *Chinese Journal of Rock Mechanics and Engineering*, vol. 36, no. S1, pp. 3578–3586, 2017.

[16] G. Han, Z. Yu, R. Liu, Q. Tang, X. Wang, and L. Song, “Infuence of surface roughness on shear behaviors of rock joints under constant normal load and stiffness boundary conditions,” *Natural Hazards*, vol. 2, pp. 1–18, 2022.

[17] S. Yu, H. Li, X. Gan, M. Zhang, M. Xue, and J. Li, “Comparative experimental study on calcium oxide, calcium hydroxide, and calcium carbonate solidified zinc-contaminated red clay,” *Geofluids*, vol. 2022, Article ID 8428982, 9 pages, 2022.

[18] S. Yu, M. Zhang, H. Li, Y. Yang, X. Chen, and J. Li, “Effect of chromium ion on the strength characteristics and damage law of red clay,” *Geofluids*, vol. 2022, Article ID 8451476, 22 pages, 2022.

[19] Y. Song, J. Wang, X. Chen et al., “Study the effects of dry-wet cycles and cadmium pollution on the mechanical properties and microstructure of red clay,” *Environmental Pollution*, vol. 302, p. 119037, 2022.

[20] *Geotechnical Test Method Standard*, GB/T50123-2019.

[21] The United States Environmental Protection Agency, *Solidification/Stabilization Use at Superfund Sites*, Office of Solid Waste and Emergency Response, Technology Innovation Office, Washington DC, 2000.