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# Chemical Stabilization of Diesel Contaminated Soil Using Ordinary Portland Cement: Performance Properties Aspect

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The petroleum contaminated soil treated by chemical solidification/stabilization with cement (S/S cement) can be used to backfill the road base and shallow foundation. In order to ensure the stability of the solidified petroleum contaminated soil in use, it is necessary to systematically study the performance properties of the solidified soil. To this end, the systematic laboratory experiments were conducted in this paper. It focuses on the performance properties of solidified petroleum-contaminated soils with different diesel content, curing time and cement content. The experimental results show that the unconfined compressive strength (UCS) of solidified soil decreases with the increase of petroleum contents, and increases with the increase of cement content; after 28 days of curing, the effect of cement solidification is obvious, and the strength value of soil samples increases rapidly. Besides, combined with a large number of UCS tests, the empirical equation for predicting the performance properties of cement-solidified diesel contaminated soil in high compatibility with the actual test is fitted. This provides a theoretical basis for the actual engineering in the future reuse of diesel-contaminated silty clay.

## 1. Introduction

With the rapid development of the petroleum industry, the pollution problem caused by oil spills has become more and more serious. Oil spills not only cause pollution of water bodies and air, but also result in environmental pollution and ecological damage when entering the soil. Moreover, the movement of pollutants in the soil may also cause pollution to groundwater. Thus, it is urgent to study and control petroleum-contaminated soil. It has become a hot research topic to repair and dispose of contaminated soil in a reasonable way (Khalladi et al., 2009) and reduce its harm to the environment (Scherrer and Mille, 1990).
At present, the remediation methods of contaminated soil mainly include soil replacement method, solidification/stabilization method (Taha and Alsharef, 2018), chemical leaching, biological restoration, and agricultural ecological restoration etc. (Yin et al., 2007). Studies have shown that lime (Al-Mutairi, 1995), dust (Al-Rawas et al., 2005), cement (Carrigy, 1967) and other additives (Ola, 1991) can reduce oil seepage and be used to stabilize oil-contaminated soils. Therefore, in the existing solidification/stabilization repair projects, inorganic materials such as cement are mostly used to solidify the contaminate soil (Li et al., 2018). In this way, the cementing materials such as cement are mixed with the contaminated soil, and physical and chemical means are used to prevent the pollutants in the soil from further spreading to the surroundings, thereby bringing the harmful substances to an environmentally acceptable stable solid material. After the petroleum-contaminated soil is solidified with cement, it can be used to backfill the filling and shallow foundation of the road base layer and realize the reuse of contaminated soil resources (Ola, 1991). Compared with the ordinary soil, the reuse of the petroleum contaminated soil should consider more factors. It is necessary to systematically study the performance properties of the soil after solidifying the petroleum contaminated soil, so as to ensure its stability after curing. Now, scholars have systematically studied the strength characteristics of conventional cemented soil (Mitchell et al., 1972), and proposed some strength prediction methods for cemented soil (Horpibulsuk et al., 2003). However, there have been few studies on the performance properties prediction method of diesel-contaminated cemented soil.

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In order to study the performance properties of cement-solidified petroleum contaminated soil, this paper selects diesel as a typical petroleum hydrocarbon pollutant. Through the unconfined compressive strength test, it studies the effect of the diesel content, curing time and cement content on the performance properties of the cured product. Also, the empirical equation for predicting the performance properties of cement-solidified diesel contaminated soil in high compatibility with the actual test is fitted, which provides a theoretical basis for the actual engineering in the future reuse of diesel-contaminated silty clay. This also has important practical significance and application value for guiding engineering construction and protecting the environment.

## 2. Experimental materials and methods

The petroleum contaminated soil sample in the experiment was artificially prepared in the laboratory, and the soil sample was the silty clay taken from Changchun City, China. After oven-dried at 105 °C for 24h, the soil was screened over 0.5 mm sieve (the silty clay with the clay content less than 5 μm was 20.4 %, that with the silt content of 5-75 μm was 77.7 %, and that with the content over 75 μm was 1.9 %); the liquid and plastic limits were 39.9 % and 21.9 % respectively. The data indicate that silt and clay are the main particle fractions, the plastic index of the soil is 18.0 and, based on the Unified Soil Classification System (ASTM 2011a), the soil is classified as CL. The diesel used belongs to light diesel oil, and its viscosity was much less than that of crude oil. Besides, it had the diesel density of 0.840 g/cm$^3$, the freezing point of -10 °C, the kinematic viscosity of 3.0-8.0 mm$^2$/s (20 °C), the viscosity 3-4 times of the water, and good flow performance. Contaminated soil samples with oil content of 4 %, 8 %, 12 % and 16 % were prepared separately (the oil content was calculated according to the ratio of the oil quality to the quality of the dry soil). The samples were numbered O4, O8, O12, and O16. Cement soil without diesel is denoted by O0. Due to the good fluidity of diesel, soil samples can be directly mixed with diesel to form artificially contaminated soil samples, and sealed for one week to ensure sufficient physical and chemical reactions between diesel and soil samples (Khosravi et al., 2013). The cement used in the experiment was ordinary Portland cement 325, and the dosage was 0 %, 3 %, 5 %, 8 %, and 10 % of the dry soil weight, denoted by C0, C3, C5, C8, and C10 respectively. The material, as prepared above, was transferred to a compaction mould and a compaction test was conducted according to ASTM D-698(ASTM2011b), to determine the maximum dry density and optimum moisture content of the samples. Samples for further unconfined compression tests (UCT) were prepared in the mould using static compaction at the determined maximum density and optimum moisture content and cured for 7, 14 and 28days in sealed plastic bags to prevent loss of moisture. The UCT was conducted on the cured samples after different curing periods.

## 3. Experimental results and analysis

### 3.1 Strength characteristics of cement-solidified petroleum contaminated soil

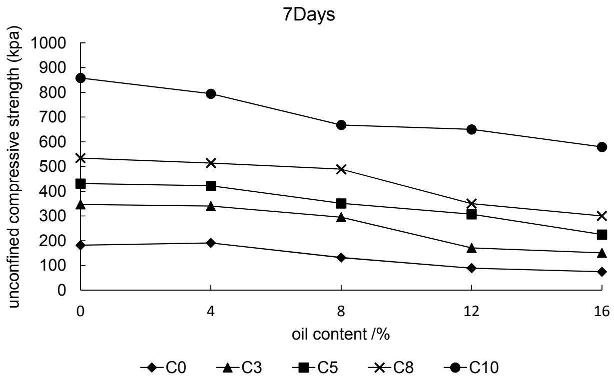
Table 1 lists the test results of UCS with different cement content, diesel oil content and curing time. It can be seen from the test results that the strength of the oil-contaminated soil samples after cement solidification has increased to varying degrees.

*Table 1: Unconfined compressive strength of samples (kPa)*

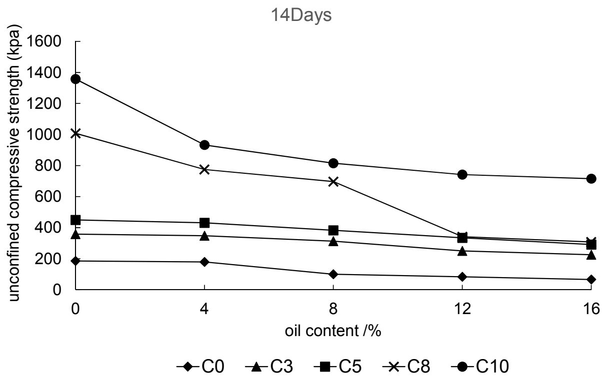
| Cement content | Curing time | Oil content (%) | | | | |
|---|---|---|---|---|---|---|
| (%) | (days) | O0 | O4 | O8 | O12 | O16 |
| C0 | 7 | 182 | 191 | 132 | 89 | 151 |
| | 14 | 185 | 179 | 100 | 83 | 225 |
| | 28 | 182 | 142 | 100 | 84 | 250 |
| C3 | 7 | 347 | 340 | 295 | 171 | 225 |
| | 14 | 358 | 348 | 313 | 250 | 291 |
| | 28 | 387 | 370 | 358 | 280 | 312 |
| C5 | 7 | 431 | 422 | 351 | 307 | 300 |
| | 14 | 450 | 431 | 383 | 335 | 308 |
| | 28 | 489 | 472 | 450 | 338 | 333 |
| C8 | 7 | 534 | 514 | 489 | 350 | 579 |
| | 14 | 1008 | 775 | 697 | 342 | 716 |
| | 28 | 1217 | 892 | 775 | 463 | 933 |
| C10 | 7 | 858 | 794 | 668 | 650 | 151 |
| | 14 | 1358 | 933 | 816 | 742 | 225 |
| | 28 | 1457 | 1358 | 1242 | 1192 | 250 |

Unconfined compressive strength (UCS) is one of the important indexes to evaluate the efficiency of a given stability method (the US Environmental Protection Agency, 2000). ASTM d-4609 (ASTM 2011c) indicates that for a treatment to be considered effective, unconfined compressive strength of 345 kPa or more must be achieved.

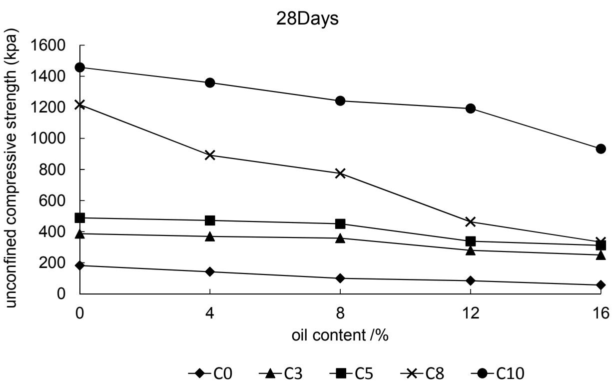
The UCS versus cement content (cement content of 0 %, 3 %, 5 %, 8 %, and 10 %) data for samples with different levels of contamination (oil content of 4 %, 8 %, 12 % and 16 %), at different curing ages (7, 14 and 28days), is shown in Figure 1, which is based on the data in Table 1.




*(a)*




*(b)*




*(c)*

*Figure 1: UCS v. oil content of samples with different levels of cement content at different curing times: (a) 7 days; (b) 14 days; (c) 28 days.*

Under the condition of different curing ages, the strength variation law of contaminated soil samples is approximately the same. Without cement addition, Figure 1 shows that there nearly is no change caused by curing time in the uncontaminated samples. With the cement content increasing, the strength of contaminated soil samples with low pollution level (oil content value less than 8 %) was greatly improved by cement solidification. When the oil samples with more serious pollution (oil content value greater than 8 %) were affected by diesel oil, their reinforcement strength after mixing cement was improved slightly. With the same cement content, the strength value of the soil sample decreased with the increase of diesel oil content, which shows the inhibition effect of diesel oil on cement solidification, and the inhibition effect increases with the increase of diesel oil content. The mechanism of cement solidification is based on its own hydrolysis and hydration reaction, and ion exchange, agglomeration, hard coagulation reaction, carbonation with soil particles etc. In addition, various gel products of cement hydration are continuously filled to fill the pores in the soil, so as to reduce the pores in the soil and increase the compactness. Under the combined influence above, the soil particles were further agglomerated, solidifying and enclosing the contaminants in a narrow space to form a solid block. The presence of diesel fuel causes the above reaction of cement to be retarded at a certain stage, and it cannot fully exert its own effect, ultimately weakening the cement reinforcement effect.

The UCS of cement-solidified contaminated soil increases with the increase of curing time, which is related to the hydration reaction process of cement. With the increase of curing time, the hydration reaction, ion exchange, agglomeration reaction and hard coagulation reaction of cement have been fully developed, and various products of cement are further increased, which promotes the agglomeration of particles in the soil sample and the filling of pores. Therefore, the UCS of the soil sample is enhanced as the curing time increases.

With the increase of curing time, the weakening effect of diesel on soil, the inhibition of diesel on hydration reaction, and the hydration reaction of cement etc. were simultaneously carried out in the soil. Under the condition that various reactions were mutually restricted, the hydration product of cement stabilizes the soil sample. Despite the inhibiting effect of diesel, the strength of contaminated soil after cement solidification still shows an increase with curing time. When the cement content increased to 10 %, after 28 days of curing, the soil samples strength of different diesel contents showed a significant increase. It can be seen that the effect of cement-solidified diesel contaminated soil is significant. This method can be applied to the reuse of contaminated soil, but different projects have different strength requirements for the soil. Thus, the strength of the required site should be determined according to the actual situation, so as to determine the optimum cement content through laboratory tests.

### 3.2 Predicting UCS of cement-solidified petroleum contaminated soil

Through variance analysis for the UCS with different cement content, diesel oil content and curing time in Table 1, it can be found that the difference between the three variables and the UCS of the cured product is extremely significant. The UCS is basically exponential with the cement content, and can be fitted by the exponential Eq (1). $\alpha_c$ is the cement content, and the fitting parameters a and b are shown in Table 2.

$$q_u = ae^{b\alpha_c} \tag{1}$$

*Table 2: Fitting parameters of Eq (1)*

| | Oil content /% | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Curing time /days | O0 | | | O4 | | | O8 | | | O12 | | | O16 | | |
| | a | b | $R^2$ | a | b | $R^2$ | a | b | $R^2$ | a | b | $R^2$ | a | b | $R^2$ |
| 7 | 199.7 | 0.14 | 0.90 | 206.7 | 0.13 | 0.96 | 154.5 | 0.15 | 0.95 | 96.6 | 0.19 | 0.93 | 78.8 | 0.19 | 0.97 |
| 14 | 184.5 | 0.20 | 0.90 | 192.3 | 0.17 | 0.99 | 128.5 | 0.20 | 0.93 | 106.1 | 0.19 | 0.88 | 86.5 | 0.20 | 0.88 |
| 28 | 187.8 | 0.21 | 0.97 | 160.4 | 0.22 | 0.98 | 128.5 | 0.23 | 0.95 | 100.9 | 0.23 | 0.96 | 78.9 | 0.24 | 0.86 |

By analyzing the fitting parameters in Table 2, a is linearly related to the diesel content $\omega$, and after fitting:

$$a = -6.9299\omega + 186.72 \qquad R^2 = 0.9965 \tag{2}$$

b is linearly related to the curing time t, and after fitting:

$$b = 0.0021t + 0.1751 \quad R^2 = 0.9958 \tag{3}$$

Substituting Eq (2), Eq (3) into Eq (1), the empirical equation for predicting the UCS is fitted as:

$$q_u = (-6.9299\omega + 186.72)e^{(0.0021t + 0.1751)\alpha_c} \tag{4}$$

Where ω is the content of diesel fuel, $\alpha_c$ is the cement content, and t is the curing time. After substituting the three variables into the empirical equation, it can be found that at the 28 d curing time, the cement content at C8 greatly differ from the measured results, which is mainly caused by the parameter b. When the diesel content is 12 %, the increase of the b value suddenly decreases, making the correlation between the parameter b and the diesel content worse, because the high diesel content has seriously delayed or hindered the hydration reaction of cement in the solidified soil, and the growth law of its strength is different from that of the sample with low diesel content. For this, in this paper, the data with diesel content of 12 % was deleted, and the comparison between the corrected prediction and the test results is shown in Figure 2. Therefore, it is believed that the calculation result of the prediction equation is in good agreement with the measured results. This empirical equation has certain engineering application value.

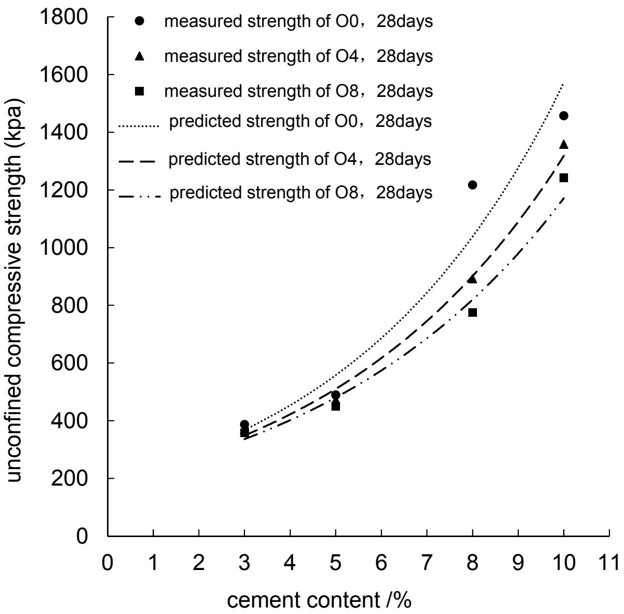



*Figure 2: Result comparison between fitting results and testing results*

## 4. Conclusions

The purpose of this study was to determine cement stabilization effects on petroleum contaminated soil and predicting the unconfined compressive strength (UCS) of cement-solidified petroleum contaminated soil. Contaminated samples with five diesel contents were stabilized by five cement addition ratios, and UCS tests were conducted on the samples. Based on the analysis of the influence of curing time, diesel content and cement content on the strength development process of stabilized soil ， the following conclusions and suggestions could be drawn.

1) The UCS of cement-consolidated contaminated soil increases with the increase of cement content, decreases with the increase of diesel content, and increases with the increase of curing time. Diesel has a certain inhibiting effect on cement solidification.
2) When the cement content increases to 10 %, after 28 days of curing, the soil samples of different diesel contents show a significant increase. The effect of cement-solidified diesel contaminated soil is significant, and this method can be applied to the reuse of contaminated soil.
3) The strength value of cement solidified soil at any time can be predicted by Eq (4); this equation is applicable to the strength prediction of of cement-solidified soil with any diesel content (0, 4, 8, 16), and with any cement content (C0, C3, C5, C8, C10) in the experiments.
4) Diesel-contaminated soil can be reused after being stabilized by cement. Different practical engineering projects have different requirements on soil strength. The strength should be determined according to the prevailing site conditions, so as to determine the optimal cement content through the strength prediction equation and laboratory test.

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