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Effect of Cationic exchange Capacity of Soil on Strength of Stabilized Soil

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Abstract

Consumption of Ca and OH in soil may cause the pore solution in the stabilized soil Ca(OH)₂ unsaturated, and thus reduces the amount of cementious hydrates generated by the cement hydration, which impedes strength growth of the stabilized soil. It is not clear that what kinds of factors have influence on Ca(OH)₂ saturation in the stabilized soil. In this research, a set of soil samples with different cationic exchange capacity were selected, stabilized soil specimens are prepared by mixing the soil samples with different proportions of cement and Ca(OH)₂. The influence of soil cationic exchange capacity on the strength of the stabilized soil are investigated by means of measuring the concentrations of main ions in the pore solutions squeezed from the stabilized soil specimens and the strength of the stabilized soil. It is revealed that: cationic exchange of the soil samples depresses the Ca(OH)₂ saturation of the stabilized soil. When the cationic exchange capacity of the soil samples is high enough, the Ca(OH)₂ concentration of the pore solution in the stabilized soil cannot get saturated, under these conditions, further cationic exchange depletes Ca²⁺, OH⁻ which shall be used to generate calcium silicate hydrate, so the amount of calcium silicate hydrate decreases, which results in the poor strength of the stabilized soil.

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Keywords: Stabilized Soil, Soil Strength, Cationic Exchange Capacity, Pore Solution, Ionic Concentration.

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Introduction

Using silicate cement series to treat soft soil foundation is a very widely used foundation reinforcement techniques. However, different with concrete, using the same cement to stabilize soils with similar physical and mechanical properties, the strength of the stabilized soil varies greatly. Even some soils with better physical and mechanical properties obtain less soil strength than those with poor properties. It is difficult to design mixing ratio of stabilized soil in engineering application. Therefore, acquisition of factors other than physical and mechanical properties is significant to engineering practice.

Reference [16] claims that cement and soil mixing, cement hydration produces calcium hydroxide (CH), calcium silicate hydrate (CSH) and other hydrates. Clay absorbs CH until saturation, and then pozzolanic reaction and physical improvement takes place between CH and clay. Effect of hydration and hardening of cement is not affected by clay and CH reaction, but controlled by pozzolanic reaction ability of clay and CH. This theory cannot explain the phenomenon that the same amount of cement cannot get same strength. It is reported that, in clay minerals, hydration of cement can be normally carried out. CH consumption of kaolinite, illite, is kind of small, so the strength of cement soil is high. CH consumption of montmorillonite is kind of large, so the strength of cement soil is reduced. In clay, other cations are adsorbed and exchanged with calcium ion. Therefore, the higher cationic exchange capacity (CEC) is, the lower strength of cement soil will be, and vice versa. Organic matter in the soil has the stronger adsorption ability about calcium ion. When the absorption is greater than a certain value, the cement soil cannot achieve a satisfied strength. Presence of soluble salt in soil has a great influence on the strength of cement soil. That study noticed that there is relationship between this phenomenon and the strength of stabilized soil. Reference [12] claims that, in the cement soil, CH is unsaturated usually. In this condition, further absorption of $\text{CaO, Ca}^{2+}$, and $\text{OH}^-$ leads to reducing of formation of cementation of hydrate like CSH. As a result, cement with same properties and amount produces different amount of hydrates, which means different strength of stabilized soil. However, it hasn’t told exactly that what factors affects CH saturation of soil and then affects soil strength.

This study selected several groups of soils with similar physical properties but different soil CEC. Add different proportion of cement and CH to prepare stabilized soil. Attempt to analyze the effect of soil CEC on the strength of stabilized soil through the determination of relationship between pore solution ion concentration and the strength of stabilized soil.

Testing materials and methods

Testing Materials. This test uses ordinary portland cement 32.5(Jingdu brand, production of Beijing Cement Factory), water, reagent grade calcium hydroxide (production of Beijing Yili Fine Chemical Products Co., Ltd.). The soil samples are kaolin (GT), Sodium montmorillonite (NT) and artificially screened silty soils (FT). All of them are production of the Beijing Chemical Plant Second Factory. Soil specimens are NT1, NT2, NT3, NT4 and GT, which are prepared according to proportion shown in Table 1. The physical and chemical properties are shown in Table 1, which indicates that the soil specimens have similar density and porosity. In Table 1, the pH value and cationic exchange capacity CEC are measured by the China University of Geosciences Chemical Testing Center, and the testing method is referenced to Reference [13].
**Testing Methods.** Use SJ-160 static slurry mixer to do the mixing as following steps: Weigh cement, water and CH as testing proportion and put them in pot. Mix 30 seconds at low mixing velocity. Put soil as testing proportion in the pot, then mix 1 minute at low mixing velocity. Shave mixture stayed on shell and blade into the pot, then mix 2 minutes at high mixing velocity.

Put the mixture in 50×50×50mm mold in three layers. Each layer should be vibrated on ZT-1×1 swing table for 1 minute.

Remove the mold 24 hours later and put the specimens into curing box. The curing temperature is 20°C ± 2 and the curing humidity is 95% ± 2. At 30d age, test the unconfined compressive strength.

Based on Jungan Xue’s design [14], a simplified and improved pressure filter is designed. Wrap the specimens with nylontafla and put it into mold of the pressure filter. Pressurize the specimens at a rate of 0.1~0.2kN/s until it reaches 300kN. Stop pressurizing when there is no effluent. Collected percolate is 30~40ml. Try to reduce as much exposure to the air as possible. Store the percolate in an airtight bottle.

Ionic concentration of each ion is measured by the China University of Geosciences Chemical Testing Center with following methods.

\[ \text{Ca}^{2+} \]: the complex titration of standard EDTA solution
\[ \text{OH}^- \]: Titration of HCL standard solution with methyl red as indicator

\[ \text{pl} \left( \text{K}^+ / \text{Na}^+ \right) \]: flame photometry
\[ \text{pH} \]: pH-3 pH meter
\[ \text{SiO}_4^{4-} \]: Silicon molybdenum blue colorimetric method
\[ \text{SO}_4^{2-} \]: Barium sulfate gravimetric method

\[ \text{Al}^{3+} \]: Titration of CaSO4 standard solution with PAN as indicator

**Testing Results CEC and compressive strength of stabilized soil.** Mix cement and CH with NT1, NT2, NT3, NT4 and GT to make stabilized soil. Cement mixing ratio, aw is 15%, 20%, 25% and 30%. Water cement ration is 0.5. 30d compressive strength of each type of stabilized soils, \( q_u \) is shown in Figure 1. Mix those soils with 15% cement and 1%, 2%, 3%, 4%, 5%, 6% CH (mass ratio of CH and wet weight, Dw), then as Figure 2 shown, it is obtained that the relationship between \( q_u \) and Dw. NS1 means it is made by mixing NT1 with cement. NS1-15 means it is made by mixing NT1 with 15% cement. NCS1 means it is made by mixing NT1 with cement and CH, and so on.
Ionic concentration measurement of each primary ion in pore solution of stabilized soil. 

Take NS1-15, NS2-15, NS3-15, NS4-15, GS-15 with \( a_w = 15\% \), NS3-20, NS4-20 with \( a_w = 20\% \), NS2-25, NS3-25 with \( a_w = 25\% \) and NS1-30, NS2-30 with \( a_w = 30\% \) as testing objects. Put those specimens into pressure filter to obtain pore solution, then test major cationic concentration. Testing results is shown below in Table 2.

| Specimens | \( a_w \) | Ionic concentration (mmol/L) |
|-----------|---------|-----------------------------|
|           |         | Na  | K   | Ca  | OH  | Al  | S   | Si  |
| NS1-30    | 30\%   | 59.912 | 26.660 | 1.442 | 119.46 | 2.076 | 0.387 | 0.631 |
| NS2-30    | 30\%   | 60.229 | 29.300 | 2.911 | 140.06 | 2.432 | 0.674 | 0.538 |

**Figure 1 Compressive strength of Stabilized Specimens**

**Figure 2 Relationship between compressive strength and CH**
### Table 2 Ionic concentration of each primary ion in pore solution of stabilized soil

| Soil Type | Ca²⁺ | SiO³⁻ | OH⁻ | Degree of Saturation |
|-----------|------|-------|-----|---------------------|
| NS2-25    | 45.455 | 12.975 | 1.081 | 127.68 |
| 25%       |       |       |      |                    |
| NS3-25    | 49.329 | 10.321 | 2.018 | 151.54 |
| NS3-20    | 28.101 | 7.322  | 0.999 | 130.36 |
| 20%       |       |       |      |                    |
| NS4-20    | 30.416 | 8.909  | 1.766 | 167.01 |
| GS-15     | 10.276 | 2.589  | 2.214 | 187.84 |
| NS4-15    | 9.257  | 2.012  | 1.534 | 158.35 |
| NS3-15    | 9.125  | 1.921  | 0.741 | 120.34 |
| 15%       |       |       |      |                    |
| NS2-15    | 9.997  | 2.011  | 0.435 | 100.21 |
| NS1-15    | 9.045  | 2.432  | 0.213 | 90.47  |

Calculation of degree of saturation of CH in pore solution of stabilized soil. In cement stabilized soil, cement hydration generates CH and CSH. CH doesn’t have direct impact on strength of stabilized soil, but CSH is an major contributer. CH exists in the pore solution as Ca²⁺ and OH⁻. CSH is generated as following thermodynamic equilibrium equation.

\[
Ca^{2+}(aq.) + xHSiO^{-} (aq.) + OH^{-} (aq.) \rightleftharpoons xCaO.SiO_2.H_2O (1)
\]

Obviously, in the pore solution, while the CH is not saturated, the generation of CSH depends on the ionic concentration of Ca²⁺ and OH⁻. In the stabilized soil percolate, the saturation of CH does not only depend on concentration of Ca²⁺ and OH⁻, but also other ions. Therefore, this article will analyze how Ca²⁺ and OH⁻ impact strength of stabilized soil under other ions' influence.

Calculate CH saturation of pore solution with various ions by methods mentioned in Reference [16], [17], and [18].

Based on data from Table 2, calculate ion activity of Ca and OH⁻. According to euqtion, \(Ca(OH)_2 = Ca^{2+} + 2OH^{-}\), LAP, ion activity product of CH, can be obtained by \(LAP = [Ca^{2+}][OH^{-}]^2\). Then, SI, the saturation index is calculated by Eq 2, and the result is shown in Table 3. In this equation, \(K_{sp}\) is thermodynamics solubility product constant. It equals to 6.3096E-6 at 25°C.
SI = \log \left( \frac{IAP}{K_{sp}} \right) \quad (2)

SI=0 indicates CH is saturated in the pore solution. SI>0 indicates CH is over-saturated. SI<0 indicates CH is not saturated.

**Testing result analysis.** From Fig 1, it can be told that the stabilized soil with lowest CEC content, GS has the highest strength while \( a_W \) is 15%. With CEC content increasing, corresponding soil strength decreases. Table 3 indicates that CH is not saturated in any specimen except for GS. In addition to this, with CEC content increasing, corresponding CH saturation decreases. If all specimens have similar physical properties, which is proved later, the soil strength will only depend on hydrates generation. All these illustrate that the ionic exchange decreases CH saturation, and a high CEC may cause unsaturation of CH in pore solution. In this condition to this, based on Eq 1, more ionic exchange consumes \( Ca^{2+} \) and \( OH^- \), which reduces CSH generation, and then leads to decreasing strength of stabilized soil. Therefore, the higher CEC, the lower CH saturation, which means that lower production of hydrates like CSH and lower strength of stabilized soil.

From Fig 2, for GT, after mixing with 15% cement, increasing CH increases little of the soil strength. On the other hand, for other sample soils, increasing CH increases the soil strength until it reaches a peak value. In addition to this, soil with higher CEC needs more CH to reach the peak value. All these are because of that the mixing of CH increases \( Ca^{2+} \) and \( OH^- \) content, which increases CSH generation and leads to increasing of soil strength. While CH is saturated, it guarantees there is enough CSH generated to make the soil gets highest strength. Higher CEC means lower CH saturation in pore solution, which means more CH is needed to offset CEC effect. From what have been discussed above, in stabilized soil, CEC reduces CH saturation, and then reduces CSH generation, which leads to decreasing of soil strength.

Moreover, in Fig 2, each soil sample mixed with 15% of cement and then mixed with CH, CH dosage reaches a certain value, the ultimate strength of each stabilized soil are basically the same. As described above, when the CH

| Specimen      | Ion activity | LAP         |
|---------------|--------------|-------------|
|               | Ca\(^{2+}\)  | OH\(^{-}\)  |
| NS1-30 NS2-30 | 0.001648     | 0.002914    | 0.04748 0.04966 | 3.7148E-6 7.1871E-6 |
| NS2-25 NS3-25 | 0.001145     | 0.002017    | 0.04877 0.05880 | 2.7231E-6 6.97301E-6 |
| NS3-20 NS4-20 | 0.001002     | 0.001651    | 0.05985 0.06504 | 3.5894E-6 6.9847E-6 |

Table 3 Saturation index of CH in pore solution
in pore solution is saturated, cement hydration can generate a sufficient amount of hydrate, which indicates that the amount of hydrates in each soil should be the same (The CH can act with silicon, aluminum to carry out hard coagulation reaction to produce hydrated calcium silicate hydrates, but compared to the hydration, it is negligible. Otherwise, in the dosage of the same cement content or identical CH, low CEC stabilized soil strength should be higher). Stabilized soil strength depends on soil physical properties and hydrate generation. When hydrates generation and soil strength is similar, it means that the physical properties of the soil samples are similar. The strength of stabilized soil is affected by varies physical properties, like soil moisture content, soil porosity, soil clay content, soil particle size, and so on. All these indicators are not quite same in the tests, however, as shown in Fig 1, for all the specimens, those physical properties have similar comprehensive influence on strength of stabilized soil, in other words, the soils have similar comprehensive physical properties.

In Fig 1, when the cement content is 20%, 25%, 30%, respectively, the soil strength increases with decreasing of CEC. However, at the points pointed out by the arrows, the soil strength hardly increases while the CEC is reduced to a certain value. The higher CEC of the soil is, the more cement is needed to reach the maximum of soil strength. Then in Table 3 it can be found that the points mentioned before, is exactly the points that CH turns to be saturated from unsaturated state. Main product of cement hydration is CH and CSH. Increase cement ratio because CSH directly provides soil strength, and it increases CH saturation to help on CSH generation to make the strength higher. Since the soils have similar comprehensive physical properties, all specimens have similar maximum soil strength. However, those stabilized soils with higher CEC need more cement to achieve the peak value of soil strength.

**Conclusion**

When the $a_w$ is 15%, only GT, which has the lowest CEC, gets CH saturated in pore solution. CEC is inversely related to CH saturation and soil strength.

For all specimens with $a_w=15\%$, they get higher soil strength when they are added in more CH. However, the soil strength stop increasing while CH is saturated. Stabilized soils with higher CEC need more CH to achieve the peak value of soil strength.

With increasing of cement ration ($a_w=15\%, 20\%, 25\%, 30\%$), the specimens get higher CH saturation. Stabilized soils with higher CEC need more cement to get CH saturated. While the cement ratio is same, those specimens with CH saturated have almost the same soil strength and those specimens with CH unsaturated have lower soil strength if they have higher CEC.

Ionic exchange reduces CH saturation. While CH is saturated, It may cause CH unsaturated if the CEC is high. While CH is unsaturated, it consumes $\text{Ca}^{2+}$ and $\text{OH}^-$, which reduces CSH generation in cement hydration, and then leads to loss of strength of stabilize soil.

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