Reinforcement techniques for collapsible loess subgrade with NaOH and CaCl₂ solutions

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Abstract. The NaOH solution can activate the surface of soil particles and solidify each other at contact points to improve the mechanical strength of soil, therefore the alkali liquor reinforcement method has the advantages of simple construction, high reinforcement strength, good water stability and low cost, and is applicable to the reinforcement of cohesive soil foundation. For loess lacking calcium and magnesium ions, CaCl₂ solution should be added and can react with NaOH to form Ca(OH)₂ hydraulic cementing material which can significantly strengthen soil. The strength of soil strengthened by NaOH and CaCl₂ double solution reinforcement is 1/3~1/2 higher than that of single liquid reinforcement. As the operating load increases, it is necessary to reinforce the subgrade of a special railway line of Jinan city under the condition of normal traffic. The upgrading double liquid method is used for reinforcement and good results are obtained.

1. Introduction
Collapsible loess is refers to under the weight of overburden stress, or under the effect of gravity stress and additional stress, because of flooding been structure damage and produce significant additional deformation of soil, and belongs to the special soil[1, 2]. Widely distributed in China's northeast, northwest, central China and east China in some parts of the loess collapsibility with more. Solutions of sodium hydroxide (NaOH) heating to 80 ~ 100 °C, by grouting pipe under the action of its weight into the soil, when calcium, magnesium ions content is higher in soil (e.g., the loess), make the soil particle surface activation and cementation, which makes soil strength and water stability was improved. In 1965, a three-storey dormitory building built on a collapsible loess foundation in Xi‘an city, the foundation was successfully strengthened by alkali solution reinforcement method. Three months after the reinforcement, the measured maximum settlement amount was only 8mm [3]. The building remained stable and the reinforcement effect was good. The Soviet union also carried out indoor and outdoor experiments in the early 1980s, and the results were very good. The alkali liquor reinforcement method has been recognized as a promising method to improve the foundation bearing capacity and eliminate the loess collapsibility.
A special railway line in jinan has been put into operation for more than 20 years. Due to the upgrading of transport vehicles, the cargo load increased by 2.84 times. It is shown that the railway foundation of this section is a collapsible loess, and the subgrade pressure has exceeded the initial collapsible loess after the upgrade operations. Therefore, it is necessary to strengthen the foundation of this railway roadbed.
The commonly used methods to treat collapsible loess foundation include cement - sodium silicate grouting reinforcement[4], dynamic compaction[5], plain soil pile compaction, water immersion treatment, and lime soil filling. Experimental study had been completed for engineering properties of loess reinforced by lignosulfonate, and mechanisms had been drawn that the main reasons for improvement of engineering characteristics of loess by calcium lignosulfonate are soil particles cementing and pore filling[6]. As the normal use of transportation lines is required during foundation treatment, the above conventional methods are difficult to implement [7]. According to the test results of the chemical content of the foundation soil, the alkali liquid grouting reinforcement and the alkali liquid and calcium chloride double-liquid grouting reinforcement were respectively used in the test section for comparative study. The reinforcement scheme of double fluid grouting is finally selected, and the monitoring shows that the treatment effect is very effective.

2. Physical and Chemical Properties of Soil
The substratum below the roadbed is mainly loess silty clay, which is brown yellow, plastic, wet ~ saturated and has small wormholes. It has vertical joint, ferromanganese oxide and occasionally silt. With the level 1 non-gravity collapsibility, the subsidence usually occurs at a depth of less than 4m. The mainly physical and chemical properties of the soil layer are shown in Table 1.

| Natural water content (%) | Dry density (g/cm³) | Plastic index Ip | Clay content (%) | Standard penetration number (n) | Ca²⁺ content (mg/100g soil) | Mg²⁺ content (mg/100g soil) |
|--------------------------|--------------------|-----------------|-----------------|-------------------------------|-----------------------------|-----------------------------|
| 23                       | 1.31               | 11              | 32              | 6.5                           | 0.33                        | 0.286                       |

3. Grouting Reinforcement Test
3.1. Principle of chemical reinforcement
The existing methods of chemical reinforcement in soil are that the chemical solution is poured into the soil, the dispersed soil particles will be cemented by the gelling material separated out from the solution itself, so that the soil can be strengthened. Silicification and polymer solution reinforcement are widely used chemical reinforcement methods at home and abroad.

When NaOH solution (alkali liquor for short) is used to reinforce soil, the reinforcement mechanism is totally different from the above silicification and polymer solution reinforcement method. The NaOH solution itself cannot separate out any cementitious substances, and its function is to activate the surface of the soil particles and solidify each other in contact (in the presence of calcium and magnesium ions), thus improving the mechanical strength of the soil. Experiments show that only when the soil has a high specific surface area, the alkali solution can effectively reinforce the soil[8]. Therefore, it is mainly applicable to the reinforcement of cohesive soil foundation.

The following chemical and physical chemical reactions occur mainly in NaOH solution into the soil.
At first, the substitution reaction of soluble and exchangeable alkali soil gold was carried out, which resulted in the hydroxide of alkali soil metal on the surface of soil particles. Such as:

\[
2\text{NaOH} + \text{Ca}^{2+} \rightarrow 2\text{Na}^+ + \text{Ca(OH)}_2 \downarrow
\]

Then the free state of SiO₂ and Al₂O₃ in soil and the fine particles of soil (aluminosilicates) react with NaOH to form sodium silicate and sodium aluminate in solution state. Under the action of NaOH solution, the surface layer of soil particles aluminosilicate will gradually expand and soften, that is, transform from solid phase to liquid phase gradually, so the adjacent soil particles can more closely contact with each other in this process, and the surface will be mutually soluble. But only the action of NaOH solution, the soil particles between this kind of dissolution cementation sodium aluminosilicate cementation is non-water stability. Only under the condition that the soil particles are surrounded by Ca(OH)₂ can this cementite become a complex complex with high strength and water hardness. Depending on the formation of these complexes, the soil particles can be firmly cemented together, and the soil can be consolidated. Its mechanical strength is greatly improved and it has sufficient water stability. In short, the strengthening effect of alkali solution on soil mainly depends on NaOH solution.
to make the surface of soil particles to fuse with each other, and under the action of calcium and magnesium ions, this kind of cement can be solidified. A large amount of test results showed that high temperature solution can obviously increase the effect on soil. When the content of calcium and magnesium ions in the loess is large, only a single solution is needed to obtain a good reinforcement effect. In this way, CaCl$_2$ can interact with part of NaOH in soil to generate Ca(OH)$_2$ required for soil consolidation, and part of CaCl$_2$ can also directly interact with sodium aluminosilicate complex (the reaction product of NaOH and soil particle surface) to form hydraulic cementation [9]. Such as:

\[
2\text{NaOH} + \text{CaCl}_2 \rightarrow 2\text{NaCl} + \text{Ca(OH)}_2 + \text{Na}_2\text{O} \cdot n\text{SiO}_2 \cdot m\text{Al}_2\text{O}_3 \cdot x\text{H}_2\text{O} \\
\text{Na}_2\text{O} \cdot n\text{SiO}_2 \cdot m\text{Al}_2\text{O}_3 \cdot x\text{H}_2\text{O} + \text{CaCl}_2 \rightarrow 2\text{NaCl} + \text{CaO} \cdot n\text{SiO}_2 \cdot m\text{Al}_2\text{O}_3 \cdot x\text{H}_2\text{O}
\]

Under the same conditions, the strength of the soil reinforced by double liquid method is 1/3~1/2 higher than that of the soil reinforced by single liquid method.

### 3.2. Grouting test arrangement

In order to obtain the reasonable parameters of railway subgrade reinforcement and ensure the safety of railway operation after reinforcement, 6m of this subgrade is selected as the test section. The plane layout of the test section for grouting reinforcement is shown in Fig. 1, the spacing of the grouting holes is 0.5m*0.5m, the depth of the grouting holes is 3.0m and the diameter is 110mm.

![Figure 1. Grouting test plan.](image)

Design parameters of single-fluid grouting reinforcement is 100g/L NaOH solution with the dosage of 50kg/m$^3$. Related study and engineering cases due to improper proportion of NaOH and CaCl$_2$ solution, the Ca$^{2+}$ ion content is low, causing the grouting effect is not ideal [10], therefore increased the dosage of Ca$^{2+}$ ions during the experiments and the double liquid grouting parameter are 70g/L NaOH solution with the dosage of 35kg/m$^3$ and 100g/L CaCl$_2$ solution with the dosage of 30kg/m$^3$. During actual construction, grouting can be stopped when the slurry infusion speed is less than 1L/min and lasts for more than 5min.

It is proved that temperature is the most important factor for the reinforcement speed or strength of soil. Therefore, preheating the solution before perfusion is a very effective and necessary measure to improve the effect of soil reinforcement. When steam is added for a certain period of time, the strength of soil reinforcement will be further improved. The lye (or calcium chloride) left near the perfusion...
holes can also be pushed to the periphery to make it fully usable. Therefore this experiment adopts 100 °C steam to heat the grout.

4. Analysis of Test Results
After 28 days of grouting construction, the core sample of reinforced soil was obtained by drilling with a geological drill. Meanwhile, standard penetration test was conducted on the reinforced soil to analyze the reinforcement effect of the two methods.

4.1. Compressive strength of reinforced soil
In total, 6 groups of reinforced soil core samples were obtained, with two core samples in each group, respectively carrying out the unconfined compression strength test for 28 days water immersion and without water immersion. The test results are shown in Table 2.

| Grouting type        | Average of non-immersed test strength (kg/cm³) | Average of immersed 28 days test strength (kg/cm³) |
|----------------------|-----------------------------------------------|---------------------------------------------------|
| Single fluid grouting| 6.52                                          | 8.01                                              |
| Double fluid grouting| 9.55                                          | 9.92                                              |

It can be seen from the test data that the effect of double-fluid grouting is stronger than single-fluid grouting, and its compressive strength increases by about 46%. This result is closely related to the addition of Ca²⁺ ions, which fully reflects that more hydraulic cementing materials are generated and the cementing ability of soil are enhanced.

4.2. Standard penetration test
Three boreholes were arranged in two test areas for the standard penetration test, with the depth of 0.5m, 1.5m, 2.5 and 3.5m. After field test, the results are shown in Table 3.

| Depth(m) | Standard penetration number of single fluid grouting area (n) | Standard penetration number of double fluid grouting area (n) |
|----------|--------------------------------------------------------------|-------------------------------------------------------------|
| 0.5      | 9.0                                                          | 11.0                                                         |
| 1.5      | 9.67                                                         | 13.0                                                         |
| 2.5      | 9.33                                                         | 12.67                                                        |
| 4.0      | 6.0                                                          | 6.67                                                         |

According to standard penetration test result, after NaOH solution grouting reinforcement the standard penetration number increased 3, the soil strength increased obviously, but with double liquid reinforcement the effect is more ideal, standard penetration number is more than single fluid grouting 2-3. On the other hand, grouting reinforcement effect in the vertical formation is evener, within the scope of reinforcement of soil strength was improved; But the grouting hole under 1.0 m in the soil strength did not change, this is because cohesive soil permeability coefficient is small, grout failed to reach below 1.0 m at the bottom of the bore.

5. Conclusions
With the increase of soil depth the collapsibility of loess reduce gradually, the depth is greater the collapsibility response is smaller and the nature of the construction project is the better. For the road, especially need to reinforce the upper part of the loess, so as to satisfy the operating requirement. Due to the lack of calcium and magnesium ions, the subgrade soil through the test section showed that only using lye grouting can improve soil strength, but it is not enough to meet the requirements of
vehicle loading late, therefore decided to adopt the lye and calcium chloride solution of double fluid grouting to reinforce and construction parameters are the same as the test section. Grouting construction as shown in Fig. 2. After completion of construction, heavy-duty train on grouting reinforcement subgrade railway operation as shown in Fig. 3.

![Figure 2. Grouting construction site.](image1)

![Figure 3. Heavy-duty train operation.](image2)

Through the collapsible loess foundation reinforcement, lye and calcium chloride double fluid grouting reinforcement effect is completely feasible, to avoid the shortcoming of the pure cement reinforcement or lye strengthening, and obtains more evenly within the depth of grouting reinforcement effect, increase the bearing capacity of loess foundation nearly doubled, to meet the operation requirements of heavy-duty train.

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