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# Mechanical properties of stabilized saline soil as road embankment filling material

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**Abstract.** In northern China, abundant summer rainfall and a higher water table can weaken the soil due to salt heave, collapsibility, and increased moisture absorption, thus the chlorine saline soil (silty clay) needs to be stabilized prior to use in road embankments. To optimize chlorine saline soil stabilizing programs, unconfined compressive strength tests were conducted on soil treated with five different stabilizers before and after soaking, followed by field compaction test and unconfined compressive strength test on a trial road embankment. In situ testing were performed with the stabilized soils in an expressway embankment, and the results demonstrated that the stabilized soil with lime and SH agent (an organic stabilizer composed of modified polyvinyl alcohol and water) is suitable for road embankments. The appropriate addition ratio of stabilized soil is 10% lime and 0.9% SH agent. SH agent wrapped soil particles, filled soil pores, and generated a silk–like web to improve the moisture stability, strength, and stress–strain performance of stabilized soil.

**Keywords:** in situ testing; moisture stability; road embankments; stabilized saline soil; unconfined compressive strength

## 1. Introduction

The saline soil disposal depending on the type of salts present. For example, in inshore, chlorides salt is more dominant and the faster soluble in water (Wei *et al.* 2020, Shen *et al*. 2022). Saline soil in coastal north China is silty clay with many chlorides salt, which has significant moisture adsorption properties. In conditions of abundant summer rainfall and higher water table, the strength and stability of soil are reduced due to salt heave, collapsibility, and moisture absorption. (Berkowitza *et al*. 2018, Okonta *et al.* 2022). Voids between the soil particles would be generated, and that lead to variation in the molecular composition of soil skeleton. Which causes rearrangement in soil particles and decreasing the soil bearing capacity for buildings founded on it, resulting of decreasing of soil strength and stress–strain performance and occurring sudden and unexpected subsidence, and thus the structural problems existence for buildings and facilities (Yousif and Mustafa 2020, Ramesh *et al.* 2022, Wang *et al*. 2022).

Adding stabilizers improves the physical and mechanical properties of the soil, to the point where it can satisfy specifications for use in road embankments (Abdi *et al.* 2016, Gilazghi *et al*. 2016, Esmaeili *et al*. 2016, Kannan *et al*. 2022,). Previous studies have shown that stabilizer content was the primary influencing factor on the mechanical properties of the stabilized soil (Jin *et al*. 2021, Pastor Navarro *et al*. 2023). For example, in one study, the lime content used for improving silt and clay was generally in the range 3–9%, and lime–cement has been used as a stabilizer, in a ratio of 1:2 (Baldovino *et al.* 2018, Sukmak *et al.* 2023). In another study, the strength and durability of expansive clay treated with varied cement and lime addition ratios increased significantly, and an optimal addition ratio was 8% cement and 4% lime (Phanikumar and Raju 2020, Shivanshi *et al.* 2023). California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) tests on soil stabilized with lime indicated that 6% lime was enough to satisfy the stabilized soil specifications, and that the fine particles had cemented into a large aggregate, which reduced the stabilized soil's plasticity while increasing its strength (Abdallah *et al*. 2023). Other studies have reported that, when lime and pozzolanic ash were added to soil, in the ranges 0–8% and 0–20% respectively, its consistency, degree of compaction, CBR, and linear shrinkage were considerably enhanced (Driss *et al.* 2023, Sukmak *et al.* 2023).

Although the addition of lime, cement, and pozzolanic ash increased the strength of saline soil, the strength, and the stress–strain performance of stabilized soil after soaking could not satisfy engineering specifications in particular geo–environments. This indicated that attention needed to be focused on the cementing strength between soil particles, and on the hydrophobicity of soil particles in wet environments.

In recent years, organic stabilizers have been added to soils, to increase the strength, moisture stability, and the stress–strain performance of the stabilized soil, through wrapping, filling, and ion exchange processes, which

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resulted in improving the hydrophobicity of the stabilized soil (Toprak *et al*. 2021, Zhang *et al*. 2022, Amir *et al.* 2023). For example, Baghini *et al*. (2014) investigated the long–term performance of subgrade soil treated with carboxylate styrene–butadiene emulsion and cement, and the results demonstrated that the UCS, flexural strength, and CBR of the stabilized soil before and after soaking improved significantly. Unconfined compressive strength test results for stabilized loess, with the addition of BCS (a soil stabilizer based on cement), proved that the strength and the stress–strain performance of the stabilized soil after soaking increased with the BCS content (Bozbey *et al.* 2021).

SH agent is an organic stabilizer invented by Lanzhou University in China, and protected by Chinese Patent Law. It has been shown that the UCS for stabilized loess increased significantly with SH agent addition (maximum strength increased by 100%), as the SH agent content increased from 0.3% to 1.35%. After soaking, the UCS for stabilized sand with SH agent was noticeably enhanced, and a desert surface treated with SH agent became completely sealed by an SH agent film (Chai 2006). A field rainfall simulation experiment was performed to test the loss amounts of soil particle, and testing results demonstrated that SH agent increased the erosion resistant and permeation resistant characteristics of the stabilized soil (Wang *et al.* 2018).

In this study, to optimize the stabilizing programs and to confirm the suitable stabilizer addition ratio, unconfined compressive strength (UCS) tests were conducted on saline soil treated with different additives or a combination of different additives, including lime–saline soil (L–S), cement–saline soil (C–S), cement–lime–saline soil (C–L–S), SH–lime–saline soil (SH–L–S), and SH–cement–lime–saline soil (SH–C–L–S). On the bases of the results of the UCS tests, field compaction tests were performed on a trial road embankment, then some field tests were carried out to verify the stabilization effect. Next, 75 m and 150 m embankment sections of the Cangzhou–Huanghua Harbor Expressway (Hebei Province, China)—from chainages K80 + 550 to K80 + 625, and K80 + 250 to K80 + 400—were constructed, using SH–L–S and L–S respectively. After curing for 7 days, in situ testing, including degree of compaction, CBR, Benkelman beam rebound deflection, and rebound modulus, were conducted to assess the suitability of the stabilized saline soils for use in an expressway embankment.

## 2. The UCS test

### *2.1 Materials*

#### *2.1.1 Soil*

Saline soil collected from Huanghua Harbor in Bohai Gulf (China) was air dried and sieved (2 mm); its physical parameters are presented in Table 1.

Table 1 Physical parameters of the saline soil

| Physical parameters | Value |
|---|---|
| Specific gravity | 2.71 |
| Salt content (%) | 2.64 |
| Grain size distribution | |
| Gravel (%) | 0 |
| Sand (%) | 6.4 |
| Silt (%) | 72.2 |
| Clay (%) | 21.4 |
| Atterberg limits | |
| Liquid limit (%) | 34.4 |
| Plastic limit (%) | 20.5 |
| Plasticity index | 13.9 |
| Optimal moisture content (%) | 20.3 |
| Maximum dry density (g/m$^3$) | 1.75 |

#### *2.1.2 Lime and cement*

Hydrated lime passing the 2 mm sieve was used in this study. The compressive strength of the cement was 32.5 MPa. The main compositions of the lime and cement, as advised by the manufacturers, were as listed in Tables 2 and 3.

Table 2 Lime composition

| Composition | Value |
|---|---|
| Available calcium and magnesium content (%) | 82 |
| Residue weight after 2 mm screen (%) | 5 |
| Moisture content (%) | 2 |
| Other (%) | 11 |

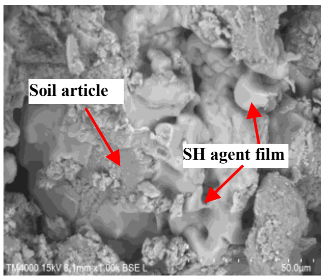
Table 3 Cement composition

| Composition | Value |
|---|---|
| CaO (%) | 63.3 |
| $SiO_2$ (%) | 21.4 |
| $Al_2O_3$ (%) | 3.3 |
| Other (%) | 12 |

#### *2.1.3 SH agent*

SH agent is made of modified PVA and water, its properties are presented in Table 4. Hydroxyl and carboxyl are presented in its macromolecular chain, and the backbone is a hydrophobic macromolecule chain linked by C–C bonds. SH agent can generate a film and a silk–like web in the soil, after air drying. Once the film has formed, it is insoluble when immersed in water. The image of SH agent and SH agent film in soil are shown in Fig. 1.

(a) SH agent in natural




(b) SH agent film in soil

Fig. 1 SH agent

Table 4 SH agent properties

| Number average molecular weight | Solid content | Color | Toxicity | State | Solubility |
|---|---|---|---|---|---|
| 20,000 | 6% | Transparent | Non | Soluble liquid | Insoluble after drying |

Table 5 The tested stabilizer addition ratios

| Stabilized soil | Cement (%) | Lime (%) | SH agent (%) | Number of specimens |
|---|---|---|---|---|
| C–S | 4, 6, 8, 10, 12 | — | — | 90 |
| L–S | — | 2, 4, 6, 8, 10,12 | — | 108 |
| C–L–S | 2C+8L, 3C+7L, 4C+6L, 5C+5L, 6C+4L | | — | 90 |
| SH–L–S | — | 10 | 0.3, 0.6, 0.9, 1.2, 1.5 | 90 |
| SH–C–L–S | 6 | 4 | 0.3, 0.6, 0.9, 1.2, 1.5 | 90 |

## *2.2 Test conditions and sample preparation*

### *2.2.1 Test conditions*

The testing machine, model of CBR–2, was made by Nanjing Soil Instrument Co. Ltd, in Nanjing, China. The test was conducted at the strain rate of 1 mm/min. The tested stabilizer addition ratios were listed in Table 5.

### *2.2.2 Preparing specimen*

Specimens were 61.8 mm in diameter, and 125 mm in height. The moisture content of soil was 20%, and the dry density is 1.68 g/cm³, that is 96% of the maximum dry density.

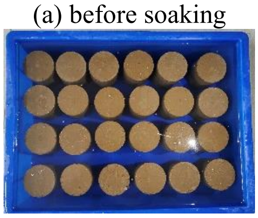
The specimens were prepared by controlling the total mass of the mixture in accordance with the standard for geotechnical testing method of the People's Republic of China (GB/T50123–2019). In order to maintain the basic stability of the dry density of the mixture, the stabilizer was added to the soil, and the mass of saline soil was reduced at the same time. The steps for preparing specimens were as follows: firstly, the soil was weighed according to its dry density, the water (dry soil mass of 20%) was sprayed into the soil, and the soil was mixed and sealed for 24 hours. Next, the stabilizer (hydrated lime and cement) was weighed according to the mix ratio and added to the soil, and water (stabilizer mass of 30%) were added to the mixture to meet the requirement for the chemical reaction of the lime and cement. The mixture was compacted by static compression in three layers, the specimen making equipment and demolding equipment are shown in Fig. 2.

(a) Specimen making equipment

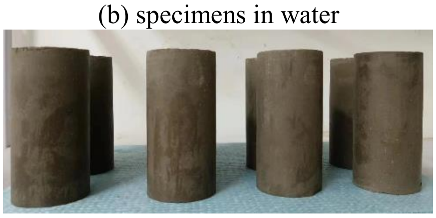
(b) Specimen demolding equipment

Fig. 2 Specimen making equipment and demolding equipment

(a) before soaking



(b) specimens in water

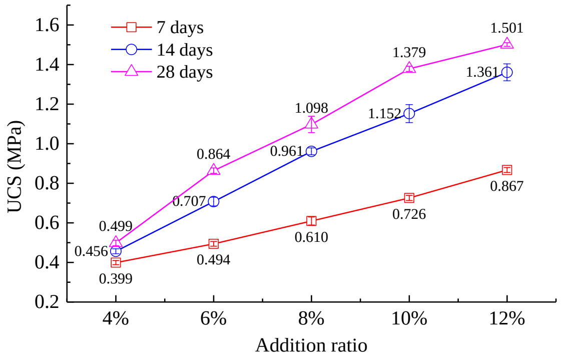


(c) after soaking

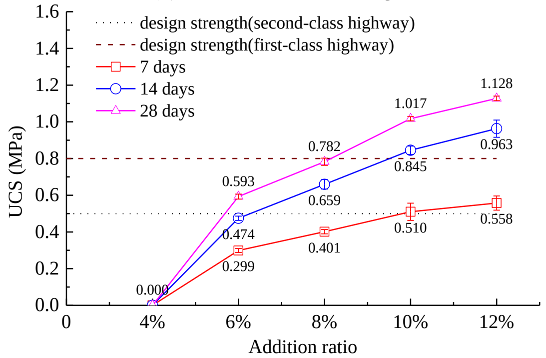
Fig. 3 Images of specimens before and after soaking

To avoid the formation of a weak surface in the course of preparing specimen, the first layer of the mixture was compacted for five minutes, and then its upper surface was deeply scraped with a cutter, and the second and third layers were added into the mold, and each also compacted for five minutes, respectively. Finally, the specimen was taken out from the mold, and was put into the curing room with a temperature of 20 °C and a humidity of more than 80%. Six specimens were prepared for each group. The tests were conducted after curing for 7, 14, and 28 days, respectively. During the preparing and curing specimen, the dry density and moisture content of the specimen were basically stable.

To assess the moisture stability of the stabilized soils, half of the specimens were cured for 7, 14, and 28 days following soaking for 1 day, respectively, and then the unconfined compressive strength test was conducted immediately. Some Images of specimens before and after soaking are shown in Fig. 3. To ensure test data reliability, six specimens were prepared for each group, and mean value and standard deviation of UCS were calculated.




(a) L–S before soaking




(b) L–S after soaking

Fig. 4 The UCS of L–S before and after soaking vs lime addition ratio

Untreated saline soil specimens were also prepared and tested as control specimens to confirm the effectiveness of the stabilizers.

### *2.3 Test results and discussion*

#### *2.3.1 UCS*

(1) L–S

Before and after soaking, the relationships between UCS and various lime addition ratios are shown in Fig. 4.

The UCS of saline soil was 0.266 MPa, and the UCS of saline soil after soaking is zero because of specimen collapsing.

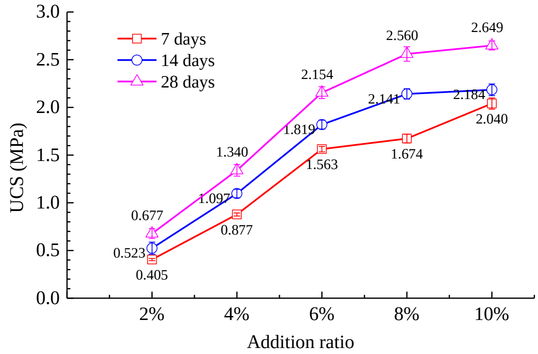
As shown in Fig. 4, the UCS of L–S increased with the various lime addition ratios, regardless of whether the stabilized soils were soaked or not. After curing for 7, 14, 28 days respectively and soaking for 1 day, the large pieces of soil specimen with 4% lime fell or collapsed, causing the integrity of the specimens to be damaged and unable to complete the UCS test, therefore their UCS was zero. Then L–S UCS increased in response to the addition of 6% and 8% lime. This indicated that a small amount of lime could not improve the moisture stability of soil.

The L–S UCS increment rates (as %), in comparison with that of saline soil before soaking (0.27 MPa), have been listed in Table 6.

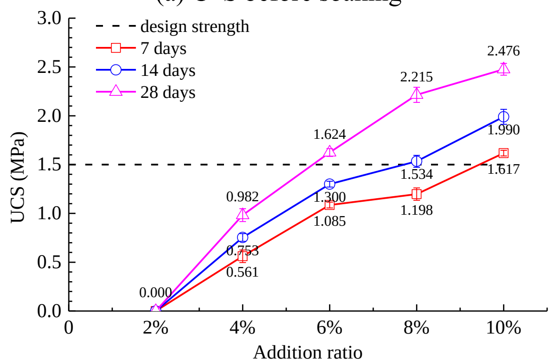
As shown in Table 6, the increment rates of the UCS increased concomitant with the lime addition ratio and curing period. The increment rates shown in the period between 7 and 14 days were more than the UCS improvement rates shown in the period from 14 to 28 days.

Table 6 The increment rates of L–S UCS in comparison with that of saline soil before soaking (%)

| Curing period | Lime addition ratio (%) | | | | |
|---|---|---|---|---|---|
| | 4 | 6 | 8 | 10 | 12 |
| 7 | 50.0 | 85.7 | 129.3 | 172.9 | 225.9 |
| 14 | 71.4 | 165.8 | 261.3 | 333.1 | 411.7 |
| 28 | 87.6 | 224.8 | 312.8 | 418.4 | 464.3 |




(a) C–S before soaking




(b) C–S after soaking

Fig. 5 The UCS of C–S before and after soaking *vs* cement addition ratio

It was also clear that the stabilizing effect of lime was more obvious in the early curing period.

Complying with the specification of Technical Guidelines for Construction of Highway Roadbases (JTG/T F20–2015), generally the L–S UCS after curing for 7days following soaking for 1 day, showed prescribed strength for use as road embankments base in China. As shown in Fig. 1(b), the UCS of L–S with 10% lime satisfied the requirements for use in second–class highway embankments, thus this addition ratio was deemed to be suitable for treating saline soil proposed for use in second–class highway embankments.

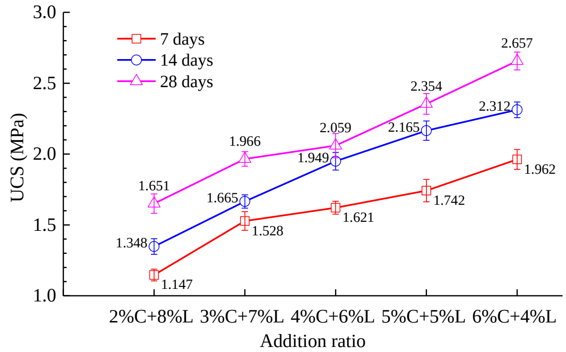
(2) C–S

The relationships between the UCS and cement addition ratios before and after soaking are shown in Fig. 5. The increment rates of C–S UCS, in comparison with that of saline soil before soaking, are presented in Table 7.

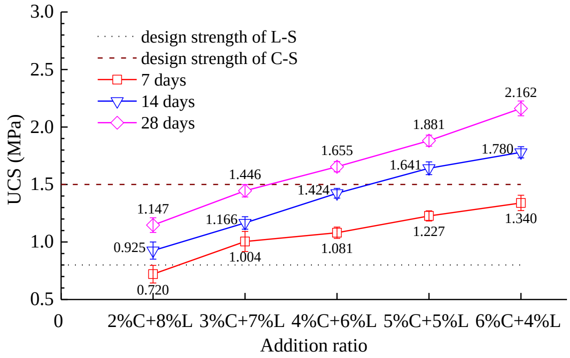
The UCS of saline soil was 0.266 MPa and zero before and after soaking, respectively. As shown in Fig. 5, before and after soaking, the C–S UCS increased with addition ratio and curing period. After curing for 7, 14, and 28 days respectively, and following soaking for 1 day, the UCS of

Table 7 The increment rates of C–S UCS in comparison with that of saline soil before soaking (%)

| Curing period | Cement addition ratio (%) | | | | |
|---|---|---|---|---|---|
| | 2 | 4 | 6 | 8 | 10 |
| 7 | 52.3 | 229.7 | 487.6 | 529.3 | 666.9 |
| 14 | 96.6 | 312.4 | 583.8 | 704.9 | 721.1 |
| 28 | 154.5 | 403.8 | 709.8 | 862.4 | 895.9 |




(a) C–L–S before soaking




(b) C–L–S after soaking

Fig. 6 The UCS of C–L–S before and after soaking vs addition ratios of cement and lime

C–S with 2% cement was zero, showing that a small amount of cement could not enhance the moisture stability of the C–S.

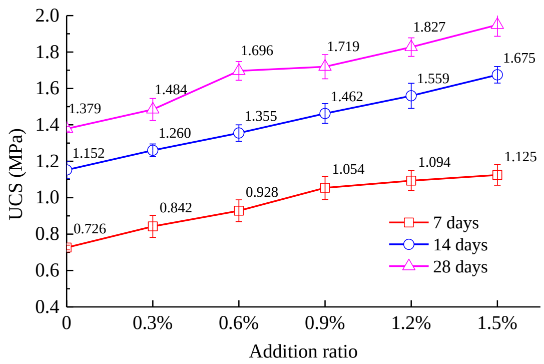
The increment rates of the UCS increased with both cement content and curing period, before soaking, and were more than those of L–S, indicating that cement influenced improvements in UCS more than lime. This confirmed that the stabilizing effect of cement was better than that of lime—a finding in agreement with the previously published results of Sharma (Sharma *et al.* 2018).

According to the specification of JTG/T F20–2015, the UCS (1.5 MPa) of C–S after curing for 7 days following soaking for 1 day achieved the standard necessary for use in the embankments base of second–class highway, first–class highway and expressway. In Fig. 2(b), the C–S UCS with 10% cement was > 1.5 MPa, making this addition ratio suitable.

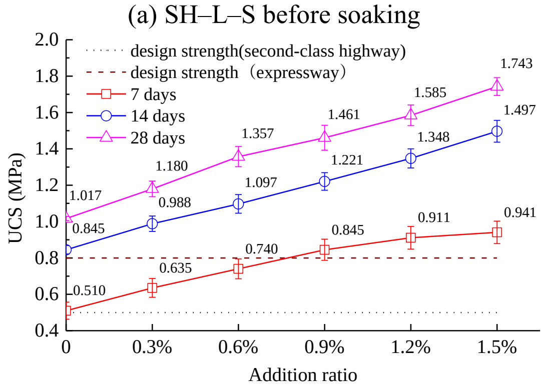
(3) C–L–S

The relationships between the UCS and the addition ratios of combinations of cement and lime before and after soaking are presented in Fig. 6.

At stabilizer addition ratios of 10%, the UCS of C–L–S




(a) SH–L–S before soaking




(b) SH–L–S after soaking

Fig. 7 The UCS of SH–L–S before and after soaking vs SH addition ratio

was consistently between that of C–L and L–S; it increased with increased cement content and decreased lime content, after curing for 7, 14, and 28 days, regardless of whether the stabilized soils were soaked or not.

According to the specification of JTG/T F20–2015, for use as first–class highway and expressway embankments base, where cement content <30% of the total amount of stabilizer, a prescribed UCS for stabilized soil, after curing for 7 days following soaking for 1 day, is 0.8 MPa, otherwise the prescribed UCS is 1.5 MPa. Therefore, the UCS of C–L–S with various addition ratios did not satisfy the requirements for application to first–class highway and expressway, while it could satisfy specifications relating to use in second–class highway—with the exception of C–L–S with 2% cement and 8% lime. After reviewing these results, SH agent was added to L–S and C–L–S, to improve the moisture stability of the stabilized soil.

(4) SH–L–S

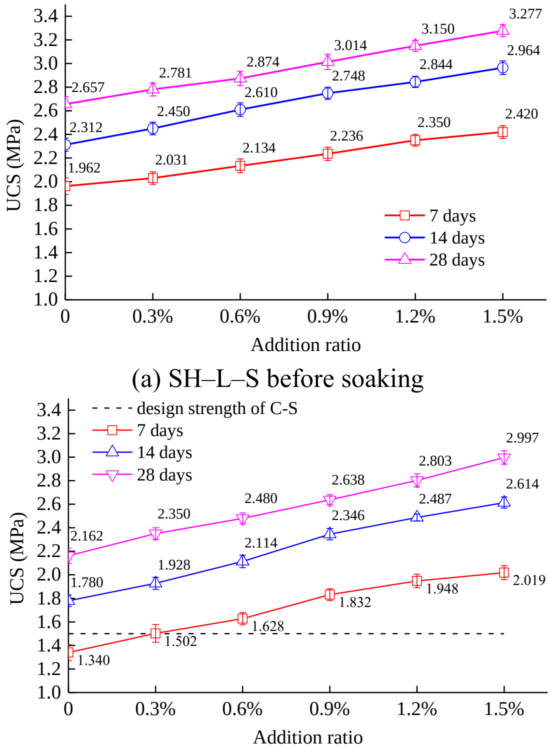
The relationships between the SH–L–S UCS before and after soaking and SH agent addition ratios have been depicted in Fig. 7.

The addition of SH agent increased the UCS of stabilized soil, regardless of whether the specimens were soaked or not. Before and after soaking, the UCS of SH–L–S increment rates compared with those of L–S with 10% lime is presented in Table 8.

It can be seen in Table 8 that the UCS increment rates increased gradually with SH agent content. Looking at the make–up of the five addition ratios, the UCS increment rates were most remarkable after curing for 7 days. It was clear that SH agent played an important role in improving

Table 8 The SH–L–S UCS increment rates before and after soaking in comparison with those of L–S with 10% lime (%)

| Curing period | SH agent addition ratio (%) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0.3 | | 0.6 | | 0.9 | | 1.2 | | 1.5 | |
| | Before soaking | After soaking | Before soaking | After soaking | Before soaking | After soaking | Before soaking | After soaking | Before soaking | After soaking |
| 7 | 16.0 | 24.5 | 27.8 | 45.1 | 45.2 | 65.7 | 50.7 | 78.6 | 55.0 | 84.5 |
| 14 | 9.4 | 16.9 | 17.6 | 29.8 | 26.9 | 44.5 | 35.3 | 59.5 | 45.4 | 77.2 |
| 28 | 7.6 | 16.0 | 23.0 | 33.4 | 24.7 | 43.7 | 32.5 | 55.9 | 41.3 | 71.4 |




(b) SH–C–L–S after soaking

Fig. 8 The UCS of SH–C–L–S before and after soaking vs SH addition ratio

the strength of stabilized soil early, particularly after soaking, which made up for the disadvantage of smaller L–S strength over a shorter number of curing periods. Therefore, it could be concluded that the addition of SH agent contributed to enhancing the stabilized soil's moisture stability. As the curing period increases, the carbonation reaction and pozzolan reaction of lime gradually strengthen. Comparing the strength of soil cured for 14 days and 28 days, it was found that the UCS increase rates was relatively smaller. Based on this, it can be deduced that the carbonation reaction and pozzolan reaction of lime weaken at curing for 28 days.

As shown in Fig. 7, the UCS of SH–L–S with 0.9% SH, after curing for 7 days following soaking for 1 day, exceeded the prescribed UCS (0.8 MPa), and therefore adding at least 0.9% or more SH agent can satisfy the specifications for application as road base for first–class highway and expressway.

(5) SH–C–L–S

The relationships between the UCS of SH–C–L–S before and after soaking and SH agent addition ratios are shown in Fig. 8

Compared with stabilized soil with 6% cement and 4% lime, adding SH agent improved the UCS, regardless of whether the stabilized soils were soaked or not. After soaking, the UCS of SH–C–L–S was more than the prescribed UCS (1.5 MPa) in JTG/T F20–2015, so when the content of SH agent is greater than 0.3%, the strength of SH–C–L–S can meet the specification requirements.

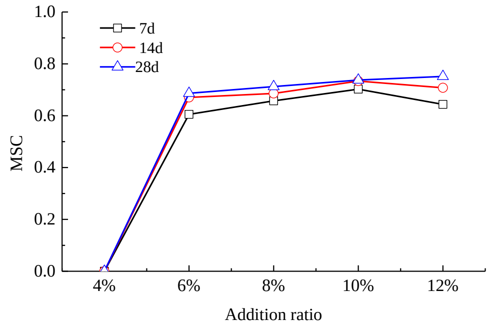
As shown in Figs. 7 and 8, the trends of the curves were similar, and the results proved that the UCS for the stabilized soils primarily resulted from chemical reactions between soil particles and stabilizers. Generally, the stabilizing effect of SH agent was to improve the moisture stability of the stabilized soils.

### *2.3.2 Moisture stability of stabilized soils*

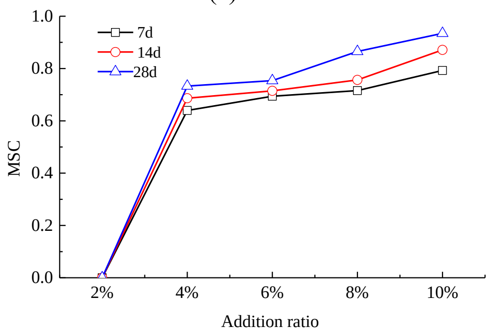
The UCS of L–S, C–S, C–L–S, SH–L–S, SH–C–S, and SH–C–L–S were evaluated before and after soaking. The moisture stability coefficient (MSC) is defined as the ratio of the UCS after soaking to before soaking. The relationship curves between MSC and addition ratio of stabilizer are shown in Fig. 9.

The MSCs of the saline soil treated with five different stabilizers increased with curing period, and the trends of their curves were similar. As shown in Fig 9 (a) and Fig 9 (b), the MSC of L–S with 4% lime, and C–S with 2% cement were zero, indicating that adding just a small amount of stabilizer could not improve the moisture stability of stabilized soils.

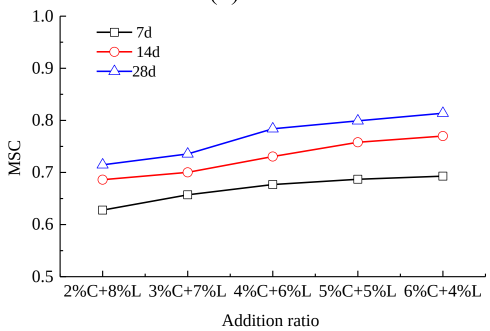
In Fig. 9(a), at 4% and 6% lime, the MSC increased rapidly, then, at 6% and 10%, the MSC slightly increased with lime content, and then stabilized at content > 10%. This indicated that stabilizer content was very important for increasing MSC, and that the MSC improved significantly at 6% lime, and 10% lime were determined to be suitable values for increasing the moisture stability of L–S. In Fig. 9 (b), the C–S MSC increased with increased cement content, particularly at more than 8% cement, and the greater the cement content, the higher the MSC. The test results did not indicate any particularly suitable cement content for the C–S MSC. In Fig. 9(c), the C–L–S MSC slightly increased with increased cement and decreased lime content, which indicated that adding a little cement could improve the moisture stability of L–S. In Figs. 9(d) and 9(e), the SH–L–



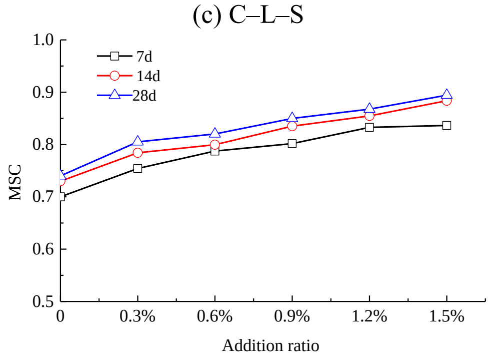

(a) L–S



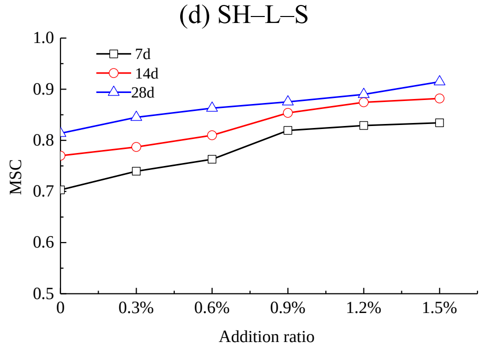

(b) C-S




(c) C–L–S




(d) SH–L–S




(e) SH–C–L–S

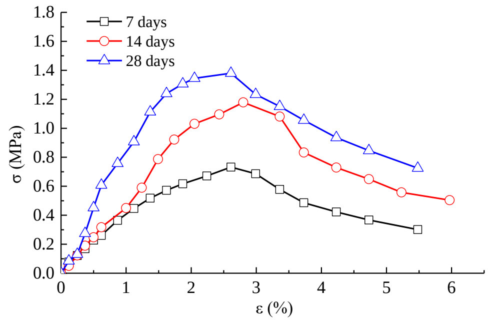
Fig. 9 MSC of stabilized soil *vs* stabilizer addition ratio

S and SH–C–L–S MSCs gradually increased with SH agent content, indicating that adding SH agent was beneficial for increasing the MSC of stabilized soils.

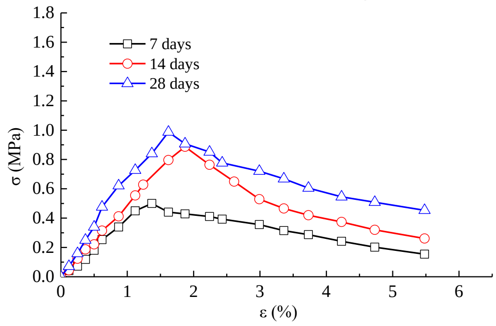
### *2.3.3 Stress–strain performances of the stabilized soil*

(1) L–S and SH–L–S

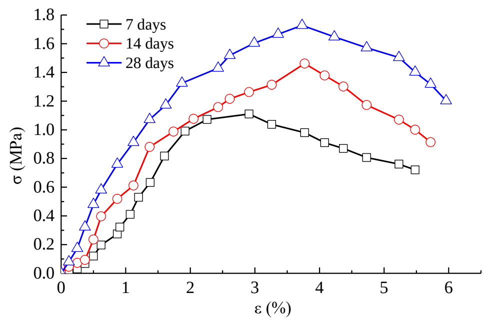
Before and after soaking, the uniaxial stress–strain relationships for L–S with 10% lime, and SH–L–S with 10% lime and 0.9% SH agent are shown in Fig. 10.



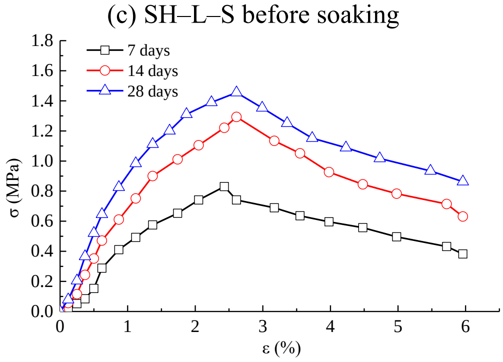

(a) L–S before soaking




(b) L-S after soaking

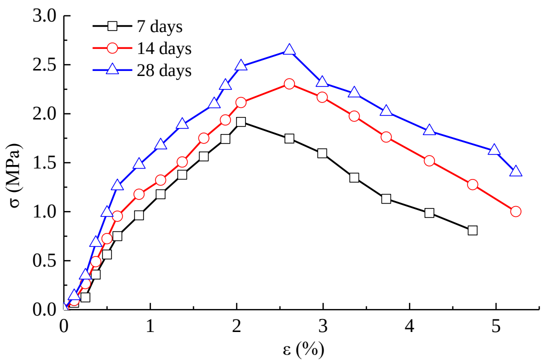



(c) SH–L–S before soaking

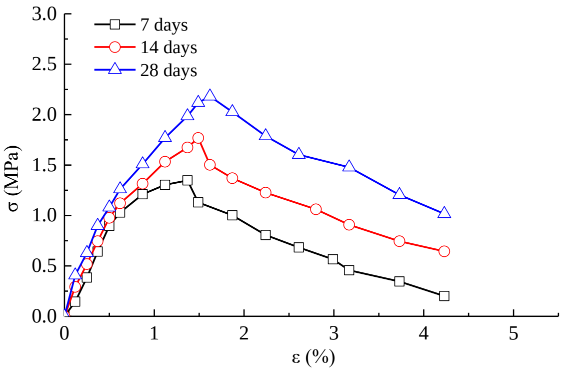



(d) SH–L–S after soaking

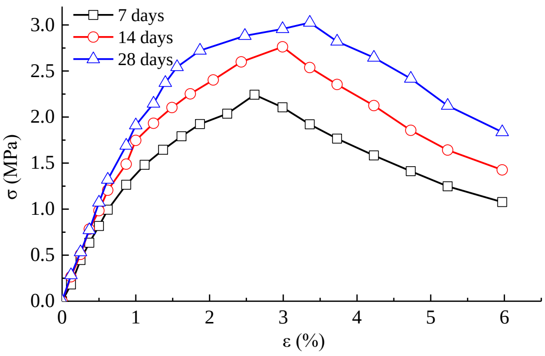
Fig. 10 L–S and SH–L–S uniaxial stress–strain curves before and after soaking



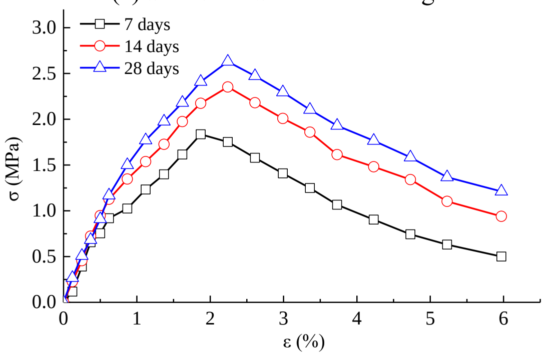

(a) C–L–S before soaking




(b) C–L–S after soaking




(c) SH–C–L–S before soaking




(d) SH–C–L–S after soaking

Fig. 11 C–L–S and SH–C–L–S uniaxial stress–strain curves before and after soaking

As shown in Fig. 10, the failure strains of L–S and SH–L–S increased with more curing period, and the stress–strain curves of L–S and SH–L–S showed strain softening. After reaching failure strain, the UCS of L–S decreased rapidly, and the strength after 5% strain was smaller; in comparison, the UCS of SH–L–S decreased slowly, and the strength after 5% strain was higher. This made it quite apparent that the stress–strain performance of SH–L–S were superior to that of L–S, regardless of whether the stabilized soils had been soaked or not.

Before and after soaking, the average failure strains of L–S were 2.67% and 1.62% respectively, while the average failure strains of SH–L–S were 3.59% and 2.55%—increases by 34.5% and 57.4% respectively, compared to L–S. These results showed that SH agent significantly improved the stress–strain performance and moisture stability of L–S.

(2) C–L–S and SH–C–L–S

Before and after soaking, the uniaxial stress–strain relationship cures of C–L–S with 6% cement and 4% lime, and the uniaxial stress–strain relationship cures of SH–C–L–S with 0.9% SH agent, 6% cement and 4% lime, are shown in Fig. 11.

Due to the stabilization affection of cement, the initial elasticity modulus and stress of C–L–S were initially larger, and the elastic strain section of the curve was steep, as seen in Fig. 11(a). After soaking, the peak stress decreased, and the average failure strains of C–L–S before and after soaking were 2.42% and 1.49%, respectively. The test results indicated that the stress–strain performance of C–L–S were clearly affected by soaking, and that the stabilized soil's plasticity weakened.

Adding SH agent increased the stabilized soil's peak stress and failure strain. The average failure strains were 3.11% and 2.12%, before and after soaking respectively, which represented increases of 28.5% and 43.5% in comparison with that of C–L–S.

The peak stress of C–L–S and SH–C–L–S were higher than those of L–S and SH–L–S, but their failure strains were lower than those of L–S and SH–L–S, respectively. These results indicated that the stress–strain performance of L–S and SH–L–S were superior to those of C–L–S and SH–C–L–S, under conditions where the same addition ratios applied, regardless of whether the stabilized soils had been soaked or not.

## 3. Field compaction test and UCS test on a trial road embankment

The test results above indicate that three types of stabilized soil, C–S with 10% cement, SH–L–S with 10% lime and 0.9% SH agent, and SH–C–L–S with 6% cement, 4% lime, and 0.3% SH agent, could satisfy with the specifications for first–class highway and expressway embankments. The UCS of L–S with 10% lime after curing 7 days and soaking 1 day could satisfy with the specifications for second–class highway.

It is noteworthy that chloride ions in saline soil are corrosive in cement, so that C–S use in road embankments may be limited if alternative stabilizing programs are available. After analyzing the UCS, stress–strain performances, and MSC of the stabilized soils, L–S with 10% and SH–L–S with 10% lime and 0.9% SH agent were selected for a field compacting test in a trial road embankment.

Table 9 The results of field compaction test and UCS test

| Soils | Curing period | Degree of compaction (%) | UCS (MPa) | | | | MSC | |
|---|---|---|---|---|---|---|---|---|
| | | | Field | | Laboratory | | Field | Laboratory |
| | | | Before soaking | After soaking | Before soaking | After soaking | | |
| Untreated soil | 0 | — | 0.28 | 0 | 0.27 | 0 | — | — |
| L–S | 7 | 96.6 | 0.92 | 0.52 | 0.80 | 0.5 | 0.57 | 0.63 |
| | 14 | 96.8 | 1.21 | 0.75 | 1.18 | 0.78 | 0.62 | 0.66 |
| | 21 | 96.8 | 1.46 | 0.95 | — | — | 0.65 | — |
| | 28 | 97.0 | 1.65 | 1.12 | 1.41 | 1.02 | 0.68 | 0.72 |
| SH–L–S | 7 | 98.2 | 1.22 | 0.85 | 1.14 | 0.83 | 0.70 | 0.73 |
| | 14 | 98.4 | 1.65 | 1.20 | 1.59 | 1.18 | 0.73 | 0.74 |
| | 21 | 98.5 | 1.74 | 1.36 | — | — | 0.78 | — |
| | 28 | 98.8 | 1.92 | 1.55 | 1.82 | 1.49 | 0.81 | 0.82 |

### *3.1 Site conditions and test results*

The site of field compaction test was located on the Yanhai Expressway, in Tanghai County, Hebei Province, China. The site was 25 m long and 3 m wide, with the L–S and SH–L–S sections each 12.5 m in length; the loose soil layer was 25 cm thick, and the compacted soil layer was 20 cm thick. Lime and SH agent were added to saline soil, mixed evenly by plough, and leveled over the road embankment surface using a road smoother. The road embankment was compacted twice by static roller, and then 4 more times using a vibrating roller.

After curing for 7, 14, 21, and 28 days respectively, the cube specimen with side length of 150 mm were prepared on–site, and then the UCS tests before and after soaking were conducted. The objectives of field compaction test and UCS test are to verify the stabilization effect of stabilizer, and access whether the strength of stabilized soil after field compaction can satisfy with the specification. The results of field compaction test and UCS test are presented in Table 9.

Table 9 showed that field test results were consistent with the laboratory test results, that is, the UCS and MSC of SH–L–S and L–S all increased with curing period. The difference of MSC between laboratory test and field test was very small. Comparing the UCS of laboratory test and field test, it was found that the UCS of L–S and SH–L–S after field compaction were slightly higher than that of laboratory test. The main reason is that the degree of compaction of specimen after field compaction is higher than that of specimen from laboratory preparing (96% degree of compaction), resulting in a higher strength of soil. In addition, during the field compaction and curing process, lime fully reacts with air and water, resulting in better stabilization effect.

After curing for 7 days following soaking for 1 day, the SH–L–S UCS was more than 0.8 MPa, which it is the minimum prescribed UCS for the embankments base of a first–class highway and expressway. These results proved that SH–L–S use in expressway embankments was feasible.

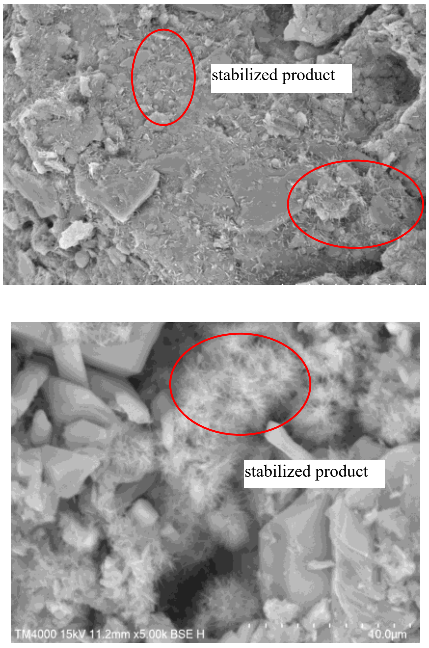



Fig. 12 SEM images of L–S curing for 28 days following soaking for 1 day

### *3.2 Discussion on stabilization mechanism*

#### *3.2.1 Lime stabilization mechanism*

The addition of lime to soil causes a series of physical and chemical reactions, which can be summarized into the following four aspects. SEM images of L–S after curing for 28 days following soaking 1 day are shown in Fig. 12.

(1) Ion exchange reaction. The $Ca^{2+}$dissociated from hydrated lime solution interacts with a large number of low cations such as $Na^{+}$ and $K^{+}$ in soil through ion exchange, resulting in a thinner diffusion layer between soil particles, a decrease in potential, and strengthening soil structure, thus the engineering properties of soil are improved.

(2) Crystallization reaction. Excessive $Ca(OH)_2$ dissolves in water and forms a supersaturated solution,

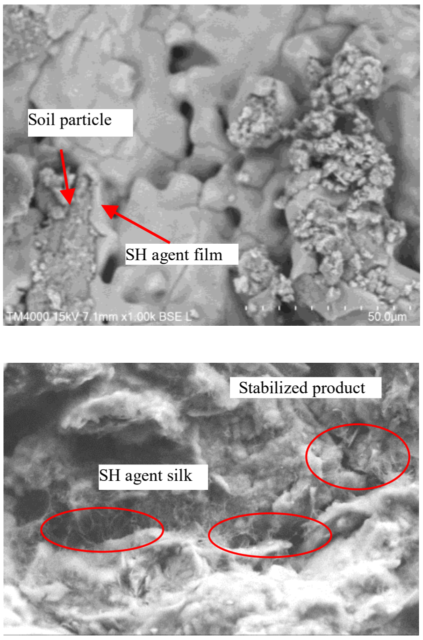



Fig. 13 SEM images of SH–L–S curing for 28 days following soaking for 1 day

which leads to the precipitation of some crystals. These crystals combine with soil particles to form soil aggregate, thereby improving the strength of the soil. The crystallization reaction is as follows.

$$Ca(OH)_2+nH_2O \rightarrow Ca(OH)_2 \cdot nH_2O \quad (1)$$

(3) Pozzolanic reaction. Lime reacts with $SiO_2$ and $Al_2O_3$ in soil to produce hydrated calcium silicate and hydrated calcium aluminate, which have high strength and good water stability. During the formation of stabilized products, the cementation between soil particles is strengthened, the pores are reduced, and the compactness of the soil increases, resulting in an increase in soil strength. The chemical reaction formula is as follows.

$$xCa(OH)_2+ SiO_2+ nH_2O \rightarrow xCaO \cdot SiO_2(n+1)H_2O \quad (2)$$

$$xCa(OH)_2+ Al_2O_3+ nH_2O \rightarrow xCaO \cdot Al_2O_3(n+1)H_2O \quad (3)$$

(4) Carbonization reaction. $Ca(OH)_2$ reacts with $CO_2$ in the air to form insoluble $CaCO_3$. $CaCO_3$ crystals are very hard and have good cementation properties, which can increase the strength of soil. In addition, the solid volume of $CaCO_3$ is slightly larger than that of $Ca(OH)_2$, so the carbonation reaction also increases the compactness of the soil and enhances its strength. The reaction formula is as follows.

$$Ca(OH)_2+ CO_2 \rightarrow CaCO_3+ H_2O \quad (4)$$

### *3.2.1 SH agent stabilization mechanism*

SEM images of SH–L–S, after curing for 28 days following soaking 1 day, are shown in Fig. 13.

Through X–ray diffraction and infrared spectroscopy testing, it was confirmed that SH agent does not occur chemical reaction with chloride saline soil and lime, and the mineral and chemical composition of the stabilized soil does not be changed. The improvement on the mechanical properties of saline soil mainly depends on the physical effect between SH agent and soil particles (Wei and Chai 2018).

SH agent addition resulted in an insoluble silk–like web and impermeable film being generated in the stabilized soil. The film wraps the soil particles, while the 3D silk–like web compact the stabilized soil structure, cementing the soil particles into aggregates, thus enhancing the cementation strength between the soil particles. In addition, SH agent fills pores, obstructing capillary passages in the stabilized soil, and weakening the hydrophilicity of the soil particles, thus facilitating a significant increase in the strength of the stabilized soil after soaking. This behavior meant that the strength and moisture stability of SH–L–S was improved in comparison with L–S alone.

## 4. In situ testing on an expressway embankment

According to the Field Test Methods of Subgrade and Pavement for Highway Engineering (JTG E60–2008), Specifications for Design of Highway Subgrades (JTG D30–2015), and Technical Guidelines for Construction of Highway Roadbases (JTG/T F20–2015), SH–L–S with 10% lime and 0.9% SH agent were used for embankments construction as part of the Cangzhou–Huanghua Harbor Expressway, Hebei Province, China. The SH–L–S sections were 75 m and 150 m in length. The thickness of the lower road embankments base was 50 cm and divided into three layers for filling. Lime and SH agent were added to saline soil, mixed evenly by plough, and leveled over the road embankment surface using a road smoother. The road embankment was compacted twice by static roller, and then 4 more times using a vibrating roller, until the degree of compaction met the requirements. The thickness of the upper road embankments base is 30 cm, and it is divided into two layers for filling.

According to Chinese specifications, some parameters such as degree of compaction, CBR, Benkelman beam rebound deflection, and rebound modulus are used to determine whether the strength and deformation of the embankment soil meet the engineering requirements. Therefore, these parameters of soil after curing for 7 days were been tested to review the quality of the expressway embankments

### *4.1 In situ testing methods*

Photos of the in situ testing are presented in Fig. 14.

(1) Degree of compaction was tested using the sand replacement method, with six points tested in the expressway embankment test sites.

(2) As shown in Fig. 14(b), CBR tests were conducted, with six points tested in the expressway embankment test sites. The test uses a jack with a maximum load of 16 public ton and a force measuring ring of 221N/0.01 mm, and the deformation is measured using a dial gauge of 0.01 mm.

Table 10 The In situ testing results

| Stabilized soil | Degree of compaction (%) | CBR (%) | Rebound deflection (mm) | Rebound modulus (MPa) |
|---|---|---|---|---|
| SH–L–S | 98.3 | 54.4 | 0.8 | 143 |
| Code value | 96 | 8, 5 | 2.5 | 33 |

(a) Compacted expressway embankment (b) CBR test (c) Benkelman beam rebound deflection test (d) Rebound modulus test

Fig. 14 in situ testing photos

(3) As shown in Fig. 14(c), Benkelman beam rebound deflection tests were conducted under a known static load. The lateral spacing between test points was 2 m and 20 points were tested in each test site section. The test used a Beckmann beam deflection instrument with a length of 5.4 m, and the deflection is measured using a dial gauge of 0.01 mm.

(4) The rebound modulus test locations were the same as those used for the CBR tests, and portable falling weight deflection meter tests were conducted.

### *4.2 In situ testing results*

The in situ testing results from the expressway embankment test sites are listed in Table 10.

In Table 10, it can be seen that the degree of compaction of SH–L–S were both > the 96% level required in the Code, and that the CBRs of the two stabilized soils were more than the values of prescribed 8% and 5% for the upper and lower road embankments base, respectively. The Benkelman beam rebound deflections was both < 2.5 mm, and the rebound moduli were both > 33 MPa.

These results indicated that the requirements of the four indices in the China's Codes for first–class highway and expressway were satisfied, meaning that the tested lime and SH addition ratios were suitable.

## 5. Conclusions

Based on the results of a series of tests, including UCS tests in the laboratory, field compaction test and UCS test on a trial road embankment, and in situ tests on an expressway embankment, the following conclusions may be drawn from this research:

(1) The strength of the stabilized soils primarily resulted from the stabilizing effects of lime, cement, and SH agent, with the latter particularly increasing the moisture stability and the stress–strain performance of the stabilized soils.

(2) The mechanical properties of the stabilized soils satisfied the China's Code requirements for first–class highway and expressway in conditions of > 10% cement. In addition, L–S with > 10% lime and C–L–S at any addition ratio meet the China's Code requirements for second–class highway embankments.

(3) The UCS for SH–L–S and SH–C–L–S with 0.9% SH agent, after curing for 7 days and soaking for 1 day, satisfied the China's Code requirements for use as an embankment base for first–class highway and expressway.

(4) SH agent wrapped soil particles, filled soil pores, and generated a silk–like web to improve the mechanical properties of stabilized soil.

(5) Four SH–L–S indices, including degree of compaction, CBR, rebound deflection, and rebound modulus, satisfied the China's Code requirements for first–class highway and expressway embankments. SH–L–S has been shown as suitable for road embankments, and 10% lime and 0.9% SH agent have been found to be the appropriate addition ratios.

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