

Experimental Study on the Pavement Performance of Cement-Improved Silty Fine Sand

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Abstract: In view of the fact that there is in shortage of superior roadbed fillers in gobi and desert areas and based on the economical and environment-friendly concept, the cement-improved silty fine sand will be used as the roadbed filler of a railway construction project, which has the engineering characteristics of difficult compaction of local silty fine sands and loose structure, within the territory of Jiuquan, Gansu Province. The test indicated that the actual silty fine sands presented relatively concentrated particle sizes in this project, the particle composition was uniform and difficult to compact. The 7d saturated unconfined compressive strength of the cement-improved silty fine sand filler was correlated with the cement content, curing age and compaction coefficient, and also showed a good linear fitting relation with the cement content. As the delay time of sample molding was lengthened, the 7d saturated unconfined compressive strength of the samples was gradually reduced, and the strength retention rate had a favorable fitting relation with the delay time of sample molding. The compaction coefficient was detected using the sand-cone method in the field compaction test, and on this basis, the “ex post detection” method was proposed to detect the compaction coefficient of this special type of fillers.

1 Introduction

For a railway construction project within the territory of Jiuquan, Gansu Province, the area that the rail track passes through mainly presents the topographic forms of desert and gobi. Due to its special geological geologic conditions and lack of superior roadbed fillers, the distant transportation scheme will cause the high engineering cost, and moreover, it fails to meet the green and environment-friendly requirements [1]. Through the comprehensive comparison and selection, the local cement-improved silty fine sands along the railway can be used as the roadbed fillers to lower the engineering cost and accelerate the project progress. In this study, a laboratory test of the silty fine sands collected on the field and cement-improved silty fine sands was firstly carried out, the value range and change laws of their physical and mechanical indexes were obtained, and on this basis, the feasibility of usage of cement-improved silty fine sands as the roadbed filler was verified through the field compaction test. In the meantime, the relationships of strength of cement-improved silty fine sand with the curing age, cement content, compaction coefficient and delay time of sample molding were summarized.

After a series of tests of silty fine sands on a highway in Dunhuang, Wang H L [1] analyzed the engineering properties and key construction technologies of silty fine

sand filler in this area by combining the stability analysis of embankment slope. Zhang B W [2] summarized the basic physical and mechanical properties of cement-improved silty fine sands through a laboratory test, and analyzed its durability. Tang Y L [3] analyzed and summarized the influencing factors of cement-improved silty fine sands. Zhang Y [4] experimentally explored the compaction characteristics of aeolian sand. Yan D F [5] studied the influence of cement-improved soil on its delay time. In an engineering practice, the laboratory test and field test were combined in this paper to systematically analyze the pavement performance of cement-improved silty fine sand.

2 Physical Properties of Soil Samples

2.1 Analysis test of silty fine sand particles

The particle size distribution curve of the representative soil sample obtained through the sieve analysis method is shown in Figure 1. According to the grading curve, the soil samples smaller than 0.075 mm accounted for 2.84% of total sample mass and those smaller than 2 mm accounted for 88%, the soil uniformity coefficient C_u was 4.55, the coefficient of curvature C_c was 1.33, so the filler gradation was poor, and the particle sizes were relatively concentrated.

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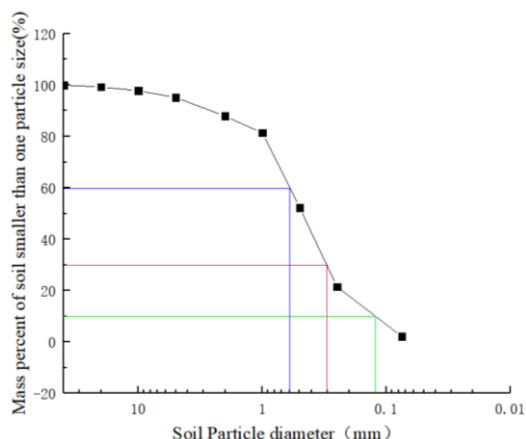


Fig. 1. Curve Chart of Particle Size Distribution.

Table 1: Summary Table of Compaction Test

Name of soil sample	Maximum dry density (g/cm ³)	Optimal water content (%)
Silty fine sand	1.96	9.7
Silty fine sand+2% cement	1.97	9.3
Silty fine sand +3% cement	1.99	9.1
Silty fine sand +4% cement	1.97	9.1
Silty fine sand +5% cement	2.02	9.0
Silty fine sand +6% cement	2.02	9.5

2.2. Compaction characteristics of silty fine sand

By reference to *Code for Soil Test of Railway Engineering* (TB10102-2010) (hereinafter abbreviated “the Code”), the mass percent of soil samples with the particle size of greater than 5 mm should be 4.8%, so the compaction test was done using the Z1 method after the air-dried soil samples passed the 5 mm standard sieve. All cement used in the test was 325[#] slag Portland cement (delayed coagulation), and the compaction results are summarized in Table 1.

Through Table 1, it could be known that:

The maximum dry density of cement-improved silty fine sand was 1.96-2.02 g/cm³ (cement content was 0-6%, dry mass ratio); the maximum dry density was positively correlated with the cement content, and the optimal water content was 9.0-9.7%.

3 Mechanical Properties of Soil Samples

3.1. Unconfined compressive strength test

By reference to *Code for Design of Railway Earth Structure* (TB10001-2016) and according to class of track, the compaction coefficient of filler beneath the bed and that on the bed bottom should be over 0.90 and 0.93, respectively. Therefore, the samples were

prepared under the compaction coefficient of 0.90 and 0.93, the sample size was 50 mm×50 mm (diameter × height), and the calculation was done through Equation (1) in the sample preparation. The samples were molded once for all, and after the molding, they were cured at temperature of 20±2°C and relative humidity of 95% for 7d, 14d and 28d. On the last day of curing age, the samples were soaked in water for 24h, and the water was 2.5 cm higher than the sample top. Next, their 7d, 14d and 28d saturated unconfined compressive strengths were measured.

$$m_{sg} = \rho_{dg}VK(1 + 0.01w_{sg}) \quad (1)$$

Where:

m_{sg} — necessary quantity of soaking mixture (g);

w_{sg} — water content of soaking mixture (%);

ρ_{dg} — dry density of chemically improved sample (g/cm³);

V —volume of test mold (cm³);

K —compaction coefficient.

Figure 2 is the histogram of unconfined compressive strength of cement-improved silty fine sand fillers under different cement contents. Under fixed compaction coefficient and curing age, the unconfined compressive strength was increased with the increase in the cement content, and the two showed a favorable linear fitting relation (correlation coefficient of linear fitting: R²=0.99625). The histogram of unconfined compressive strength of cement-improved silty fine sand filler (cement content of 3% and compaction degree of 0.90) at different curing ages is shown in Figure 3. When the cement content and compaction coefficient were certain, the sample strength at 7d, 14d and 28d was 0.484 MPa, 0.653 MPa and 0.744 MPa, respectively. It could be seen that the strength was gradually enhanced with the curing age, but the growth amplitude was gradually reduced. Figure 4 displays the histogram of unconfined compressive strength of cement-improved silty fine sand fillers under different degrees of compaction. Under certain cement content (3%) and curing age (7d), the sample strength was 0.484 MPa under the compaction degree of 0.90 and that under 0.93 was 0.529 MPa, so the strength changed somehow with the increase in the degree of compaction, but, to a small extent.

3.2 Delay time of cement-improved silty fine sand

The field construction of improved soil mainly experiences the mixing-spreading-compaction stages, the delay time of cement-improved soil refers to the time duration from the addition of the cement into the mixture until the completion of compaction, and it will generate a certain influence on the compaction quality and strength (7d saturated unconfined compressive strength) of cement-improved soil, so the time delay of improved soil is of great importance to the control of construction nodes and construction quality. Those corresponding to the field compaction of improved soil are mainly laboratory compaction test and 7d saturated unconfined compressive strength test under a certain delay time, where the latter was mainly explored in this

study under the delay time. In this test, the delay time was the duration since the cement mixing until the sample was prepared in the laboratory. To specify the 7d saturated unconfined compressive strength test under the delay time, the full amount of mixture (cement content of 3% and compaction degree of 0.90) was soaked under the maximum dry density and optimal water content obtained through the standard compaction experiment, the samples were immediately prepared, and the next group of specimens would be prepared every other half an hour after this. In the sample preparation, the calculation was carried out through Equation (1). The curing was done according to the Code, the samples were then soaked, and the saturated unconfined compressive strength of cement-improved silty fine sand filler under each delay time was measured. The relation curve between strength retention rate and time delay is seen in Figure 5. The strength retention rate was the ratio of 7d saturated unconfined compressive strength of each sample under a delay time to that under the delay time of 0.

As shown in Figure 5, the 7d saturated unconfined compressive strength of the samples was gradually reduced with the delay time, namely, the strength retention was under the gradual decline. The strength retention rate of cement-improved silty fine sand showed a good linear fitting relation with the delay time (the correlation coefficient of linear fitting: $R^2=0.983$). By reference to *Code for Design of Railway Earth Structure* (TB10001-2016) and the class of track, the 7d saturated unconfined compressive strength of chemically improved soil on the embankment beneath the bed should be not less than 200 KPa, the delay time should reach 5h or so, and the strength should be reduced to about 50% of the initial value, but the strength should still meet the code requirements, which can provide sufficient time for the field construction.

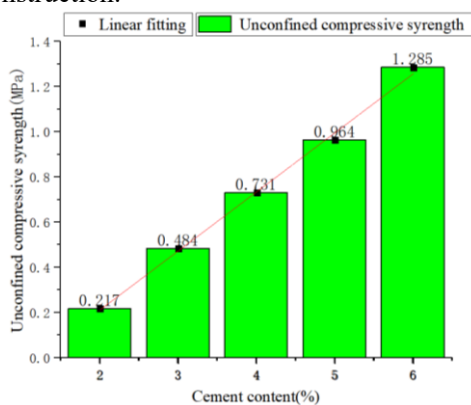


Fig.2. Unconfined Compressive Strength of Unconfined Compressive Strength of Cement-Improved Silty Fine Sand under Different Cement Contents.

4 Field Compaction Test

Restricted by the field construction conditions, the compaction test of the test segment in the field

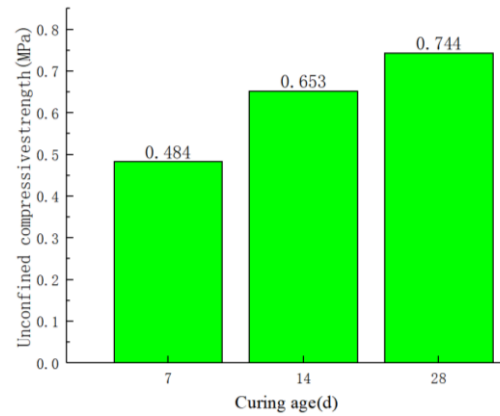


Fig.3. Unconfined Compressive Strength of Cement-Improved Silty Fine Sand at Different Curing Ages.

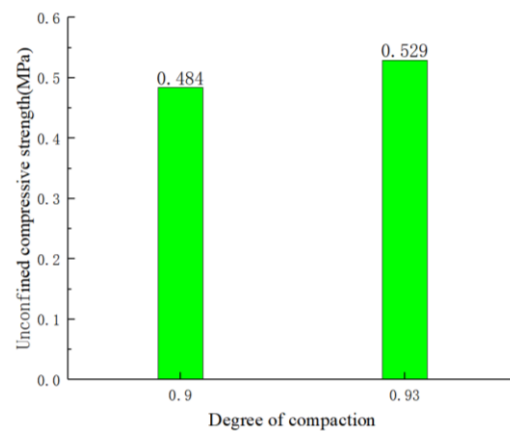


Fig.4. Unconfined Compressive Strength of Cement-Improved Silty Fine Sand under Different Degrees of Compaction.

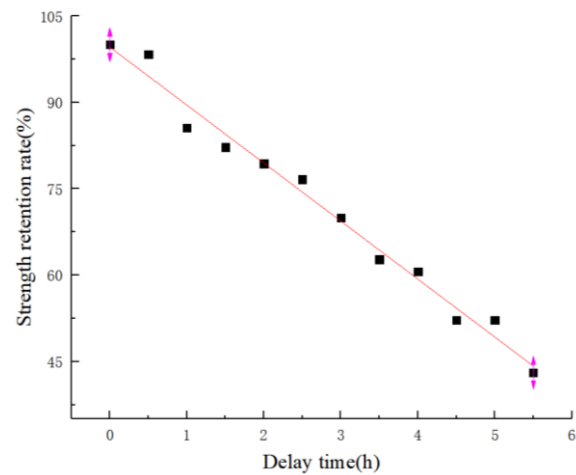


Fig.5. Delay Time-Strength Relation

construction was conducted based on the laboratory test. On the one hand, whether the compaction parameters of the fillers at the construction site met the complex standard was verified, and on the other hand, a set of the optimal construction technologies were explored. The construction efficiency was improved and the construction cost was lowered in the large-area construction. The mix-in-place was adopted in the test segment, and different loose paving thickness values (35 cm, 37 cm) and different

compaction times were set, where under five compaction times, the compaction order was static pressure→ weak vibration→ strong vibration→ strong vibration→ static pressure; when the number of compaction times was seven, the compaction order was static pressure→ weak vibration→ strong vibration→ strong vibration→ strong vibration→ strong vibration→ static pressure. According to the field compaction effects of improved fillers, the detection results could hardly reach the actual difficulty required by the degree of compaction, so the ex post detection method was used on the field, namely, after the compaction of this layer was completed, the compaction degree of filler at the next layer was detected instead of detection from the surface compaction layer according to

the sand-cone method, and the laboratory test was verified through the field compaction test, the concrete parameters of which are seen in Table 2.

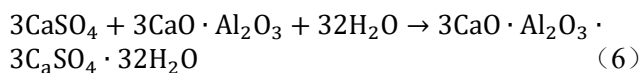
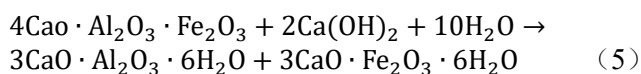
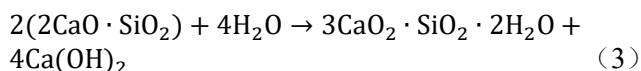
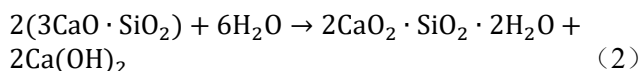
From Table 2, under a certain loose paving thickness, the number of compaction times should be increased in order to ensure the compaction quality of subgrade. When the number of compaction times was fixed, the greater the loose paving thickness, the lower the compaction quality, because the greater the loose paving thickness, the weaker the transfer of overburden pressure and vibration frequency. For the improved filler on the field, the paving thickness and number of compaction times were recommended as 35 cm and 7, respectively.

Table 2: Compaction Effects under Different Compaction Times and Loose Paving Thickness Values

Loose paving thickness (mm)	Number of compaction times	Measuring point	Compaction coefficient K	Subgrade coefficient K ₃₀ (MPa/m)
35	5	1	0.90	87
		2	0.91	80
	7	1	0.91	85
		2	0.91	92
37	5	1	0.87	87
		2	0.90	83
	7	1	0.92	89
		2	0.90	94

5 Reinforcement Mechanism Analysis of Cement-Improved Silty Fine Sand

After the cement was mixed with silty fine sands, the components in the cement would experience intense hydrolysis and hydration reactions with the moisture in the silty fine sand. The cement formed the cement hydration skeleton in all soil pores to constrain the soil particles [3]. The main chemical reactions are as follows:



Where:

3CaO · SiO₂ — main component (accounting for

40%-50%) in the cement, the main factor deciding the strength.

2CaO · SiO₂ — components with a high percent (30%-35%) in the cement, mainly generating the long-term strength.

3CaO · Al₂O₃ — the component accounting for about 6% of the cement mass, with the fastest hydration speed, being able to facilitate the early setting of cement.

4CaO · Al₂O₃ · Fe₂O₃ — the component accounting for about 10% of the cement mass, being able to facilitate the early strength.

CaSO₄ — the component accounting for about 4% of the cement mass, which can experience the hydration reaction with 3CaO · Al₂O₃ to generate cement bacillus.

5.1 Ion exchange and particle interaction

In the colloid formed through the cement hydration, Ca²⁺ and (OH)⁻ in Ca(OH)₂ presented exchange adsorption with Na⁺ and K⁺ in the soil mass, so the soil particles formed large soil blocks, and the strong adsorption capacity of Ca(OH)₂ promoted the further mutual combination of soil blocks, and a stable chain-like structure of cement soil was formed.

5.2 Carbonation



After the cement hydration, the free Ca(OH)_2 generated CaCO_3 together with CO_2 in the air, and in this process, the soil particle solidification exerted a coarse graining effect, and further enhanced the soil strength.

5.3 Hard setting reaction

With the cement hydration, a large quantity of Ca^{2+} was precipitated out of the improved soil and experienced the chemical reactions with SiO_2 and Al_2O_3 , generating water-insoluble stable crystalline minerals, such as $\text{CaO} - \text{Al}_2\text{O}_3 - \text{H}_2\text{O}$ hydration products, $\text{CaO} - \text{SiO}_2 - \text{H}_2\text{O}$ hydration products, etc.

After the improved silty fine sand filler was mixed with the cement, it was mainly adhered to the surface of sand particles. Because the particle size of a single sand was much larger than that of cement particles, the cement wrapped the surface of sand particles. As the cement hydration proceeded, the sand particles were cemented into a whole, and high strength was generated after the hardening.

6 Conclusions

(1) The fillers used in the project are silty fine sands, with the uniformity coefficient of 4.55, coefficient of curvature of 1.33, and main particle size of 0.075-0.5 mm, the particle sizes are relatively concentrated with the uniform particle composition, and they can be hardly compacted.

(2) The saturated unconfined compressive strength of cement-improved silty fine sand is related to the cement content, curing age and compaction coefficient, and the strength shows a good linear fitting relation with the cement content.

(3) The 7d saturated unconfined compressive strength of cement-improved silty fine sand is correlated with the delay time of sample molding. As the delay time is lengthened, the strength is gradually reduced, and the strength retention rate presents a favorable linear fitting relation with the delay time. At the delay time of 5h, the strength declined to a half of that at 0h, but it still meets the strength requirement, which provides favorable conditions for the construction.

(4) Due to the special engineering properties of silty fine sand, the compaction surface is still loose in the roadbed compaction process. The ex post method (sand-cone method) can be used, namely, the compaction coefficient may not be detected after the filler compaction at this layer is completed, but instead, it will be detected after the filler compaction at the next layer is ended.

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