Testing on loess collapse of expressway subgrade reinforced by lime-soil compaction piles

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Abstract: The engineering constructed on loess ground have been threatened by loess collapse upon water. In Western China a new provincial expressway now has been built on loess ground. The depth of the loess layer is more than 20 meters. The loess ground was improved by five methods to reduce the collapsibility. The reinforcement was then verified by various in-situ tests and further tests were made on laboratory to explore the effect of ground reinforcement by lime-soil compaction piles. The laboratory tests show the dry density has increased by nearly 20% and the main reason for the increase of shear strength is the increase of cohesion index by 27% when the internal friction is basically the same. The collapsibility coefficients at different depths are examined and concluded that the collapsibility has been notably eliminated. Conclusion is drawn that the expressway subgrade shall not be influenced by reinforced loess ground.

1. Introduction
China has invested many infrastructures in the western region in recent decades. One of them is Jingtai-Zhongchuan Expressway Project. It is totally 124 km long as a major part of Gansu Provincial Expressway Network. Its JZ6 contract routine is totally 13.87 km long, located in Yongdeng County and Lanzhou New District of Lanzhou City, Gansu Province, China. The concerned region is covered with loess with a thickness of more than 20 m. About 10.167-km long routine is laid on collapsible loess, mainly Malan loess prone to salinization. Routine K87 to K93 is relatively flat as irrigated land mostly. The loess can be classified into Class I or II non-self-weight collapsible loess according to Chinese loess specialized standard; Routine K93 to K104 is mostly mountainous areas with steep mountain potential, mostly self-weight collapsible loess in Grade II or above. Obviously, these loess parts should be improved before it is qualified as the ground base for railway subgrade.

Loess is well known by its collapse upon water. Many methods have been developed to reduced the influence of loess collapse. The heaven tamping, for example, is often used to compact loose loess ground with a lower water content and higher porosity [1-2]. Others such as preliminary moistening, cement, lime mixing, and chemical solidification, were widely applied on site and much experience had been gained through several decades of reinforcement of loess ground [3-8]. The purpose of collapsible loess ground improvement is to improve the nature and macrostructures of soil, reduce the permeability and compressibility of soil, control the occurrence of collapsibility, and partially or completely eliminating collapsibility.

The JZ6 contract section project has introduced 5 methods for subgrade improvement on collapsible
loess, i.e. loess replacement, vibro-compaction, heavy tamping, dynamic compaction and lime-soil compaction pile. These reinforcing methods are widely applied in China and worldwide scale [9-10]. Due to local water shortage in this loess region, the water immersion method is not suitable for this project. In this paper the reinforcement of applying lime-soil compaction pile is analyzed by experimental tests in laboratory. Collapsible test and direct shear test of loess were carried out in laboratory.

2. Ground reinforcement
Lime-soil compaction pile is a composite foundation reinforcement method, which is applicable to self-weight collapsible loess in grade II or above with the soil water content lower than 24% and saturation lower than 65% when dynamic compaction cannot be applied near existing buildings. This method uses the sinking hole method to form holes in the soil, then uses 10% lime soil to tamp and fill the piles in layers, and uses the compaction method to destroy the loose and large hole structure of the loess foundation, so as to eliminate or reduce the collapsibility of the foundation. This method is used to treat the collapsibility of foundation soil at a depth of 5 m to 15 m.

This lime-soil compaction pile diameter is 40 cm, pile length is 8 m, spacing of 1.0 m, no groundwater. Lime-soil compaction piles are bored by vibrating sinking pipe method, and are backfilled and tamped by internal hammer, with tamping energy not less than 20 kN m. Hole filler is 10% lime soil, filling layer thickness is not more than 35 cm, moisture content deviation plus or minus 2%, organic matter content is not more than 5%, soil particle size is not more than 1.5 cm, ash particle size is not more than 0.5 cm, lime calcium magnesium content is not less than 55%. Verticality deviation is not more than 1.5%, pile position deviation is 5 cm. The compaction degree of pile body shall not be less than 97%, the confidential coefficient of soil between piles shall be greater than 93%, and the minimum shall be 88%. Foundation bearing capacity test shall not be less than 250 kPa.

The effect of lime-soil compaction pile on foundation treatment is not only related to pile spacing, but also related to the thickness and width of treated soil layer. When the treatment width of soil layer is insufficient, the foundation may have large settlement or even lose stability. Therefore, the treatment width of soil layer must meet the requirements of relevant specifications. After pile formation, a 0.5-m thick lime soil cushion is set up.

![Figure 1. Construction machine for lime-soil compaction piles](image)

3. Test method

3.1. Sampling
In September, 2018, the loess blocks were taken for reinforcement by lime-soil compaction pile from several test pits excavated in the K99+407 routine of Jingzhong expressway, as shown in Figure 2. The blocks were dug at depths of 0.95 m to 1.2 m, 1.9 m to 2.1 m, 3.5 m to 3.7 m below the loess ground level. They were about 25 cm to 35 cm in size. With minimum disturbance, they were taken from the

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central zone between lime-soil piles and could be made into Class I undisturbed specimens. After the blocks were sealed and protected with good containers on site, they were transported to the laboratory.

Figure 2. On-site sampling from test pit

3.2. Basic Physical Properties of Loess
According to JTG E40-2007 "Highway Geotechnical Test Regulations", the loess was carefully tested in laboratory. The specific gravity is 2.7, plastic limit is 19.1%, liquid limit is 24.2%, and plastic index is 5.1. The particle size distribution is as shown in Figure 2 which shows for the particle size greater than 0.075 mm, its mass content is not more than 50%. The water content ranges from 5.35% to 13.14% varied with depths.

Figure 3. Particle size distribution of loess

4. Test result

4.1. Dry density
The variation of dry density at pre- and post-compaction is obtained. As shown in Figure 3, the dry density is 1.31 g/cm³ to 1.36 g/cm³ before compaction, and the dry density is 1.57 g/cm³ to 1.65 g/cm³ after compaction. The ground reinforcement effect is obvious with an increase of totally 20% in dry density. Also, it is showed that the shallow layer soil is reinforced better than that in deep layer. The porosity is 0.98-1.06 before compaction and reduced to be 0.64-0.72 after compaction. According to JTG C20-2011 Code for Geological Survey of Highway Engineering, it is considered as a “slightly dense state” before compaction, and a “dense state” after compaction.
4.2. Shear strength

Generally speaking, the soil strength will increase after compaction. Shear strength was obtained from soil specimens with depth of 3.5 m to 3.7 m. For the soil specimens before compaction, the vertical pressures are 50 kPa, 100 kPa and 200 kPa, respectively in the test. For the soil specimens after compaction, besides those pressures, an additional pressure of 150 kPa is adopted. In order to make the test result comparable, adjust the moisture content of these specimens to be basically equal. By this way, the strength differences can be related to the variation of dry density. The information of the specimen for test is shown in Table 1.

Table 1. Information of consolidated specimens at pre- and post-compaction stages

| Condition        | Sampling depth (m) | Ave. water content (%) | Ave. dry density (g/cm³) |
|------------------|-------------------|------------------------|--------------------------|
| Pre-densifying   | 3.5 to 3.7        | 26.30                  | 1.61                     |
| Post-densifying  | 3.5 to 3.7        | 25.95                  | 1.57                     |

Figure 5 shows the direct-shear strength of loess. It can be seen that the internal friction angle of loess has basically undergone no change after compaction treatment, varying from 29.6° to 30.5°. The cohesion however, has been increased from 29.74 kPa to 37.86 kPa by nearly 27%. This shows that cohesion is influenced by compaction treatment on loess strength while the internal friction angle does not. Although this figure is plotted from the test result of samples taken at depth of 3.5 m to 3.7 m, it can be acceptable to derived that the strength index of the shallower soil is improved with similar trend.

Figure 5. Comparison of strength indexes from direct shear test on loess
4.3. Collapsibility Improvement

According to the geological information, the loess involved in this section is classed as self-weight collapsible loess in Class II. Thus, the self-weight collapsibility coefficient should be taken as one of the evaluation items. Site sampling involves 3 different depths, and the average natural vertical earth pressure is about 22 kPa, 39 kPa and 67 kPa respectively calculated with a deemed fully-saturated degree of 85%. The specification recommends adding water after graded loading with an initial pressure value of 50 kPa, but this initial pressure is greater than or close to the self-weight pressure of the specimen at sampling depth. Therefore, it is not appropriate to adopt recommended test method. Here, the test scheme is to apply the calculated self-weight earth pressure on soil specimen, wait till stabilized to an axial deformation, and then immerse the soil specimen thoroughly from the specimen top. In the test, the specimens were prepared into a cutting ring by carefully cutting. The specimens were 20 mm high with a diameter of 79.8 mm. For specimens at each depth, take 3 specimens, install them on the oedometers and then apply the designated vertical pressure, immerse them with pure water and record according to JTG E40-2007 "Highway Geotechnical Test Regulations".

The test results are listed in Table 2. It can be seen that the collapsibility coefficient is very small for the reinforced soil. All these values are lower than 0.0015 which is a critical value for assessment of loess collapsibility. Obviously, the loess collapsibility has been eliminated within the sampling depth.

| Sampling depth(m) | Original specimen height(mm) | Stabilized post-immersion height(mm) | Collapsibility coefficient |
|-------------------|------------------------------|-------------------------------------|---------------------------|
| 0.95 to 1.2       | 19.778                       | 19.773                              | 0.0002                    |
|                   | 19.791                       | 19.783                              | 0.0004                    |
|                   | 19.893                       | 19.884                              | 0.0005                    |
|                   | 19.758                       | 19.754                              | 0.0002                    |
| 1.9 to 2.1        | 19.823                       | 19.821                              | 0.0001                    |
|                   | 19.713                       | 19.713                              | 0                          |
|                   | 19.708                       | 19.697                              | 0.0005                    |
| 3.5 to 3.7        | 19.806                       | 19.797                              | 0.0005                    |
|                   | 19.781                       | 19.767                              | 0.0007                    |

It can be seen in Table 1 that the self-weight collapsibility value of loess listed is far less than the value of 0.015. As the collapsibility of loess decreases with the increase of pressure, it can be inferred that under subgrade load, the collapsibility of loess is less than the collapsibility value given in the above table, and definitely less than 0.015.

5. Conclusions

The result of laboratory test on loess reinforced by lime-soil compaction piles shows that the dry density is significantly increased. The shallow loess is reinforced better than deep loess, and the self-weight collapsibility of loess is eliminated within sampling depth. For the shear strength, the inhesion index has increased obviously by nearly 27% while the degree of internal friction almost remains constant. The collapsibility coefficients are qualified in construction of expressway subgrade on loess ground.

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References

[1] Malyshev, M.V., Sidorchuk, V.F., Vutsel, V.I., et al. (1983) Mechanical compaction of loess and lacustrine-bog soils with heavy tampers. In: Proceedings of the 8th European Conference on Soil Mechanics and Foundation Engineering: Improvement of Ground. Volume 2. Helsinki, Finl. pp.791-796.

[2] Minkov, M., Donchev, P. (1983) Development of heavy tamping of loess bases. In: Proceedings of the 8th European Conference on Soil Mechanics and Foundation Engineering: Improvement of Ground. Volume 2. Helsinki, Finl. pp. 797-800.

[3] Mustafayev, A.A. (1983) Improvement in the properties of loess subsidence soils to be attained by preliminary moistening. In: Proceedings of the 8th European Conference on Soil Mechanics and Foundation Engineering: Improvement of Ground. Volume 2. Helsinki, Finl. pp. 801-804.

[4] Rzanitsyn, B.A., Chuvelev, V.K. (1983) Chemical stabilization of soils. In: Proceedings of the 8th European Conference on Soil Mechanics and Foundation Engineering: Improvement of Ground. Volume 2. Helsinki, Finl. pp. 945-946.

[5] Agha, A. (1985) Experience in Pakistan with problem soils and their improvement. In: Recent Developments in Ground Improvement Techniques. Bangkok, Thailand. pp. 563-571.

[6] Lou, G. C. (2005) Application of impact compaction technology in highway embankment of collapsible loess soils. Chinese Journal of Rock Mechanics and Engineering, 24(7): 1207-1210. In Chinese

[7] Zou, L. H., Zhao, J. C., Chen, Q. H. (2005) Experiment study on vibration to improve collapsible loess with dynamic compaction. Chinese Journal of Rock Mechanics and Engineering, 24(18): 3393-3397.

[8] Lu, X. L, Chen, Y. F. (2008) Review and new development on transmission lines tower foundation in China. In: 42nd International Conference on Large High Voltage Electric Systems 2008, CIGRE 2008., Paris, France. pp. 1-11.

[9] Xu, Y., Sun, Y. (2012) The selection of the collapsible loess foundation treatment methods. In: 2nd International Conference on Civil Engineering, Architecture and Building Materials, CEABM 2012, Yantai, China. pp. 170-173.

[10] Jefferson, I., Rogers, Evststiev, C., D., et al. (2015) Improvement of collapsible loess in eastern Europe. In: Indraratna, B., Chu, J. & Rujikiatkamjorn, C. (Eds.), Ground Improvement Case Histories: Compaction, Grouting and Geosynthetics. Elsevier Inc. pp. 215-261.