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Study on the Compaction Effect Factors of Lime-treated Loess Highway Embankments

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Abstract

This paper presents a study to investigate the effects of water content, lime content and compaction energy on the compaction characteristics of lime-treated loess highway embankments. Laboratory compaction tests were conducted to determine the maximum dry density ρ_{dmax} and optimum water content w_{opt} of loess with different lime Contents (0, 3, 5 and 8%), and to examine the effects of water content, lime content and compaction energy on the value of ρ_{dmax} and w_{opt}. In situ compaction tests were performed to obtain the in situ dry density $\rho_{in-situ}$ and the degree of compaction K of different lime-treated loess. Experimental embankments with different fill materials (0, 3, 5 and 8% lime treated loess) were compacted by different rollers during in situ tests. The results indicate that ρ_d increases due to the increase of water content w. Once water content exceeds w_{opt}, dry density ρ_d decreases dramatically. The addition of lime induced the increase of w_{opt} and the decrease of ρ_{dmax}. A higher compaction energy results in a higher value of ρ_{dmax} and a lower value of w_{opt}. The value of $\rho_{in-situ}$ achieves it's maximum value when in situ water content $w_{in-situ}$ was larger than the value of w_{opt} (+1-2%). The degree of compaction K can hardly be achieved to 100% in the field construction of embankments. Higher water content and compaction energy is needed for optimum compaction.

Keywords: Lime-treated Loess; Highway Embankments; Loess Compaction; Degree of Compaction.

1. Introduction

Loess is one of the wind deposited soils, which is widely distributed and constitute about 10% of the total land area of the world [1-3]. China has a large area of loess soil deposits in the world (about 6.3×105 km^2).The world famous Loess Plateau is located at northwest of China, which occupies more than 6% of the territory of China [4-6] (Figure 1).

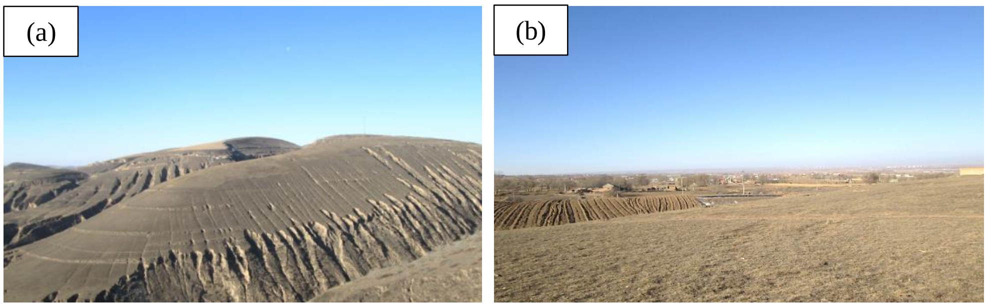

Figure 1. Loess Plateau area located at northwest of China. (a) Loess area at Yan'an city; (b) Loess area at Yulin city

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At natural state, loess has high strength and small deformation. Therefore, loess is widely used as fill materials in the construction of embankments in Loess Plateau area. However, loess is regarded as one of the worst problematic soils due to it's special properties of water sensitivity. Once loess is wetted, with the effect of geostatic stress and additional pressure, the internal structure of loess is collapsed. This phenomena is defined as water collapsibility [6-10]. Because of water collapsibility of loess, it often leads to the non-uniform settlement of loess embankments which responsible for many highway hazards in Loess Plateau area (Figure 2).

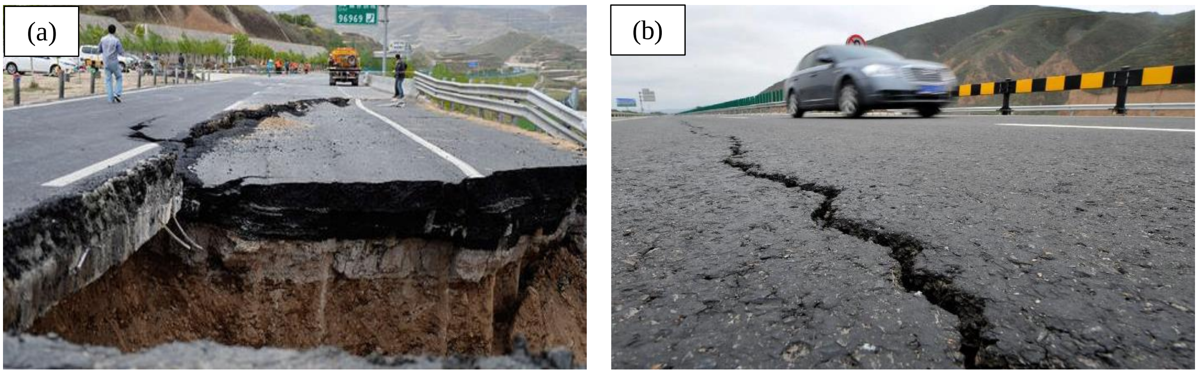

Figure 2. Highway hazards in Loess Plateau area. (a) Embankment hazards of Tianding highway; (b) Pavement hazards of Yanyan highway

In order to improve the workability and mechanical behavior of loess, lime is often added to loess as mixed fill materials of loess embankments. Lime treatment is an efficient way to improve the shear strength, plasticity and mechanical behaviors of loess through a series of physical-chemical reactions, including hydration, cation exchanges and pozzolanic reaction [11-16]. When lime is added to loess, lime induces the reduction of water content through hydration and produces large amount of. Then, it leads to flocculation due to the cation exchanges of which contributes to the increase of loess plasticity and workability. Furthermore, pozzolanic reactions induce the formation of cementitious compounds which lead to the increase of shear strength and stiffness of loess [17-22].

In the construction of loess embankments, compaction is used as an efficient technique to increase the bearing capacity and decrease the non-uniform settlement and permeability of embankments. Compaction is a mechanical process by which mass of soil, consisting of solid loess particles, air and water, is reduced in volume by the application of loads [23-32].The process of compaction increases the shear strength while decreasing the compressibility and permeability of soil. Compaction quality is largely depending on chemical composition, particle size, water content of soil and compaction method.

In the past few decades, soil compaction has received increasing attention in the geotechnical engineering. Lambe (1958) investigated the effects of different compaction conditions on the mechanical properties, such as strength, permeability and stress-strain modulus of Boston blue clay. The research results were useful for interpreting the effect of compaction condition on the mechanical properties of clay [35]. Simth and Dickson (1990) investigated the effects of vehicle weights and ground pressure on soil compaction by a series of field compaction tests. It was reported that an increase in wheel load produces a significantly increase in compaction quality [36]. Lawton, Delage and Watabe (1991, 1996 and 2000) researched the mechanical performances of compacted embankments influenced by shear strength of soils. It was shown that the shear strength of test soil has contributed to improve the compaction quality of compacted embankments [37-39]. Horpibulsuk (2008) proposed a model to describe the compaction curves of fine-grained and coarse-grained soils under different compaction energy. These curves were useful for quick determination compaction curves by using a single trial test result [40]. Jotisankasa (2009) clarified the influence of suction on the mechanical behavior of compacted silty clay by laboratory tests [41]. Patel and Mani (2011) performed a field compaction tests on sandy loam soil to investigate the subsoil compaction characteristics at ranged wheel loads and multiple passes in terms of dry density and penetration resistance [42]. Shouji (2014) presented the relationship between compaction condition and mechanical properties of saturated specimens through a series of laboratory tests [43]. These studies investigated the compaction effect factors of many kinds of soils (clay, fine-grained soils, coarse-grained soils and sandy soils) under different compaction conditions. However, the effects of water content, lime content and compaction energy on the compaction characteristics of lime-treated loess are not understood well.

In this study, a series of laboratory compaction tests and in situ tests were performed to research the compaction influence factors of lime-treated loess embankments. Laboratory compaction tests were taken to determine the effects of water content, lime content and compaction energy on the maximum dry density and optimum water content of different lime-treated loess. In situ tests were performed to obtain the in situ dry density and degree of compaction, and to study the in situ compaction characteristics of different lime-treated loess. Optimum water contents and maximum dry density of different lime-treated loess were obtained by laboratory compaction tests. The relation curves of water content and degree of compaction were obtained by in situ tests. The effects of lime content and compaction energy on the optimum water content and maximum dry density were discussed. A comparison between laboratory compaction tests and in situ tests were made to determine the effects of in situ water contents on the compaction quality of field loess embankments. Such studies would provide valuable information for the construction of loess embankments in Loess Plateau area.

2. Materials and Methods

2.1. Characteristics of Test Loess

The test loess was collected from borrow pit 1# which located at Wuding highway (Figure 3). The test loess has 89.3% of the particles are smaller than 0.075 mm and 10.7% of the particles larger than 0.075 mm (0.075-2 mm). The liquid limit, plasticity limit and Plasticity index, are 28, 15 and 13%, respectively. According to Test Methods of Soils for Highway Engineering (JTG E40-2007) [33], the test loess can be classified as low liquid limit clay. The physical properties of test loess are shown in Table 1.

Figure 3. Borrow pit 1# (located at Wuding highway)

Table 1. Physical properties of test loess

Property	Value
Liquid limit, w_L	28%
Plastic limit, w_P	15%
Plasticity index, I_P	13
Water content, w	15.6%
Particle size (0.075-2 mm)	10.7%
Particle size (<0.075 mm)	89.3%
Soluble salt content	0.20%

2.2. Laboratory Compaction Tests

2.2.1. Samples preparation

First natural loess should be air-dried and then pass through the sieve with 20 mm opening size. In order to avoid the influence of large particles on the compaction quality, all air-dried particles should be smaller than 20 mm. After drying and sieving procedure, lime was mixed with air-dried loess to obtain the predetermined lime contents (0, 3, 5 and 8%). Then water was added to each type of lime-loess mixture to reach the different target water contents (range from 8 to 16%). Finally, the obtained lime-treated loess samples were preserved at a moist container for at least 48 hours for water homogenization. Therefore, lime-treated loess samples with different water contents (range from 8 to 16%) and lime contents (0, 3, 5 and 8%) were obtained for compaction tests.

2.2.2. Laboratory test procedures

According to the Test Methods of Soils for Highway Engineering (JTG E40-2007) [33], multifunctional electric hammer apparatus (TG-007) which has a 4.5 kg rammer and a cylindrical metal mold with 100 mm internal diameter and 127 mm height was used as laboratory compaction tool to determine the relation curves between water content and dry density of different lime-treated loess (Figure 4). During the compaction tests, loess samples prepared for compaction were placed in the cylindrical metal mold with the hammer drop from a height of 450 mm. The detailed parameters of multifunctional electric hammer apparatus are shown in Table 2.

Figure 4. Multifunctional electric hammer

Table 2. Parameters of laboratory compaction apparatus

Test method		Heavy compaction
Type		II-1
Hammer diameter(cm)		5
Hammer(kg)		4.5
Drop height(cm)		45
Mold size	Inside diameter（cm）	10
	Height（cm）	12.7
Sample size	Height（cm）	12.7
	Volume（cm3）	997
Layer		5
Blows of each layer		27
Compaction energy(KJ/m3)		2687.0
Maximum grain size(mm)		20

In order to determine the effects of water content, lime content and compaction energy on the compaction characteristics of different lime-treated loess, two compaction procedures were selected in laboratory compaction tests.

The first procedure was the standard compaction test (JTG E40-2007) [33]. Different lime-treated loess samples at selected water contents and lime contents were placed in the mold in five layers and each layer was compacted by 27 blows of the rammer, with a total compaction energy of 2687 KJ/cm^3. The test results of the standard compaction tests are shown in Figure 8 and Table 5.

The second procedure was the different compaction energy test. Lime-treated loess samples used for this compaction tests were the same as that used for standard compaction tests. All samples were compacted using the same apparatus to produce five different compaction energies of 1990, 2687, 3383, 4080 and 4777 KJ/cm^3 respectively. The number of blows of every layer were 20, 27, 34, 41 and 48 respectively. The results of different compaction energy tests are shown in Figure 9 and 10.

2.3. In Situ Test

2.3.1. Test Site

The in situ test site was located at Wuding highway which cross the largest loess area of Shaanxi province (Figure 5). Loess collected from borrow pit 1# was mixed with lime, and be used as fill materials in the construction of this experimental embankment. Loess properties were the same as utilized in laboratory compaction tests. Table 3 presents the design parameters of fill materials in the construction of Wuding highway.

Figure 5. In situ test site (Wuding highway)

Table 3. Design parameters of fill materials

Subgrade	Depth (cm)	Fill materials	Minimum degree of compaction (%)
Embankment	0-40	8% lime-treated loess	96
	40-80	5% lime-treated loess	96
	80-150	3% lime-treated loess	94
	Below 150	0% lime-treated loess	93

2.3.2. In Situ Test Procedures

The experimental embankment was divided into 4 parts (100 m length and 24.5 m width of each part). Each part was divided into 5 layers of h = 25 cm in loose thickness each, which was compacted with the same compaction procedure. Loess with lime content of 0, 3, 5 and 8% were used as fill materials for different parts of this experimental embankments. In order to achieve optimum compaction, water content of each layer was determined by laboratory compaction tests (range from 8 to 16%). During in situ tests, lime was added to loess by using soil stabilizing mixer. Water was added to lime-treated loess by using sprinkling truck (Figure 6).

Figure 6. (a) Soil stabilizing mixer; (b) Sprinkling truck

After water and lime conditioning, static roller was used for the initial compaction and final compaction. Sheep-foot roller and vibratory roller were used for re-rolling (Figure 7). The compaction procedure of each layer is shown in Tab 4.The roller combination and the actual pass times of rollers utilized in this in situ tests, were determined by the technician experiences from other field embankment construction projects in Loess Plateau area. During compaction, the roller speed was kept relatively constant at average of 3 km/h. In order to achieve required level of compaction for each layer, a total of 8 compactor passes were performed.

At the end of compaction for each layer, a series of in situ tests were performed throughout the test area. The tests were included water content tests and natural density tests. Each of these tests were conducted in accordance with Field Test Methods of Subgrade and Pavement for Highway Engineering [JTG E60-2008][34].

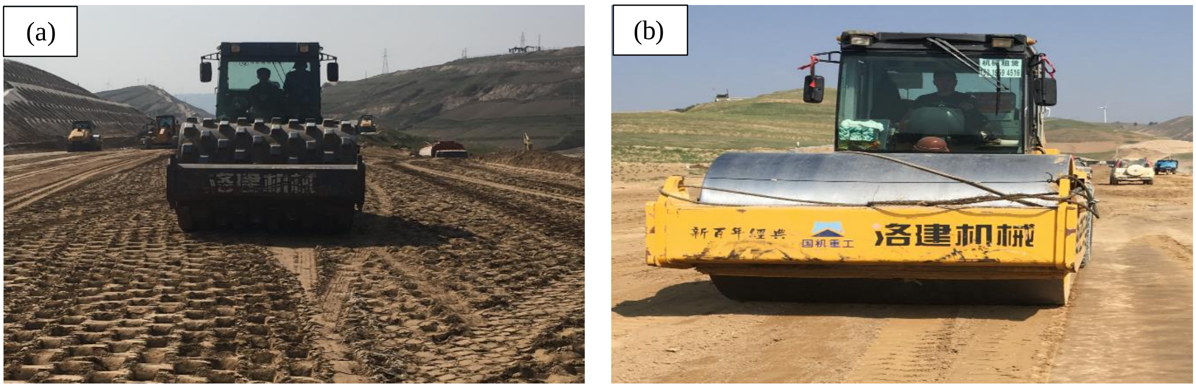

Figure 7. (a) Sheep-foot roller; (b) Static roller

Table 4. Compaction procedure for each layer

Compaction order	Roller	Pass times	Weight (ton)
1	Static roller	1	18
2	Sheep-foot roller	4	22
3	Vibratory roller	2	22.5
4	Static roller	1	18

3. Results and Discussion

Through the standard compaction tests, the compaction curves of different lime-treated loess were achieved (Figure 8). The relation curves of compaction energy and the compaction parameters (optimum water content and maximum dry density) were obtained by different compaction energy tests (Figure 9 and 10). The relation curves of in situ water content and degree of compaction were determined by in situ tests (Figure 12). In the following, the effects of water content, lime content and compaction energy on the compaction parameters (optimum water content and maximum dry density) of different lime-treated loess will be researched. The degree of compaction of field loess embankments and the comparison of compaction curves obtained from laboratory tests and in situ tests will be discussed.

3.1. Effect of Water Content

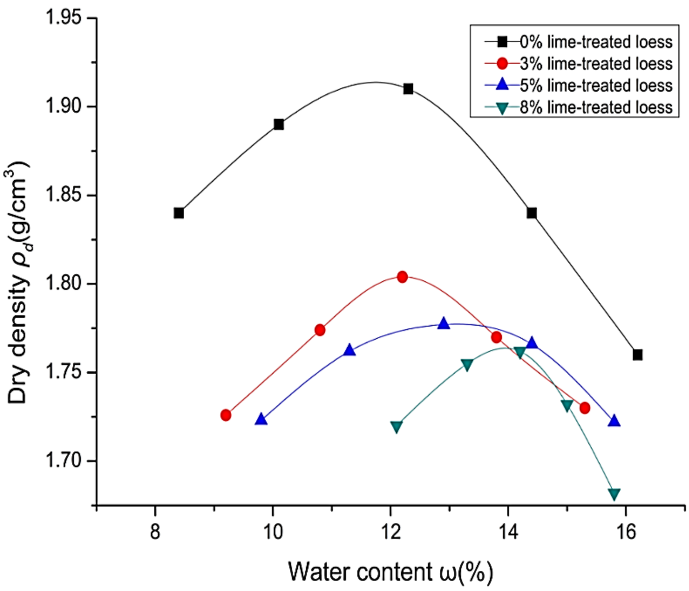

Figure 8. Compaction curves of different lime-treated loess samples

Table 5. Optimum water content and Maximum dry density of different samples

	0% lime-treated loess	3% lime-treated loess	5% lime-treated loess	8% lime-treated loess
w_{opt} (%)	11.7	12.2	12.8	13.6
ρ_{dmax} (g/cm^3)	1.91	1.795	1.777	1.764

Figure 8 shows the compaction curves of dry density ρ_d and water content w of different lime-treated loess under the total compaction energy level of 2687 KJ/cm^3.As it can be seen, for different lime-treated loess samples, with the increase of water content w, the dry density ρ_d of each sample increased until it reached it's maximum value. The maximum value is defined as the maximum dry density ρ_{dmax} and the corresponding water content is defined as optimum water content w_{opt}. As it can be seen, for all different lime-treated loess, dry density ρ_d decreases once water content w exceeds optimum water content w_{opt}.

3.2. Effect of Lime Content

The effect of different lime contents on the compaction characteristics of different lime-treated loess are also illustrated in Figure 8 and Table 5. It is shown that the shapes of compaction curves of different lime-treated loess samples were similar. For different lime contents of 0, 3, 5 and 8%, the optimum water content of lime-treated loess samples were 11.7, 12.2, 12.8 and 13.6% respectively. The corresponding maximum dry density of each optimum water content were 1.91, 1.795, 1.777 and 1.764, respectively. It is note that, the addition of lime induces the increase of optimum water content w_{opt} and the decrease of maximum dry density ρ_{dmax}. When lime is added to loess, water content reduces due to the process of hydration and evaporation. In addition to this process also increases the flocculation of loess particles and produces cementitious compounds which leads to the decrease of loess plasticity. Therefore, the mixed particles become more difficult to be compacted. With the increase of lime content, more water will be needed to obtain the optimum compaction.

3.3. Effect of Compaction Energy

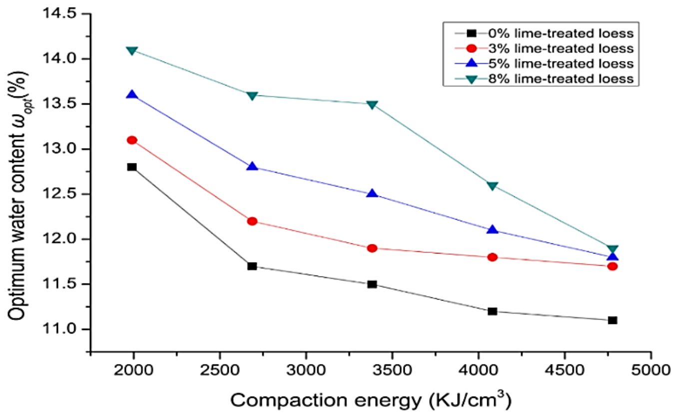

Figure 9. Relation curves of compaction energy and optimum water content

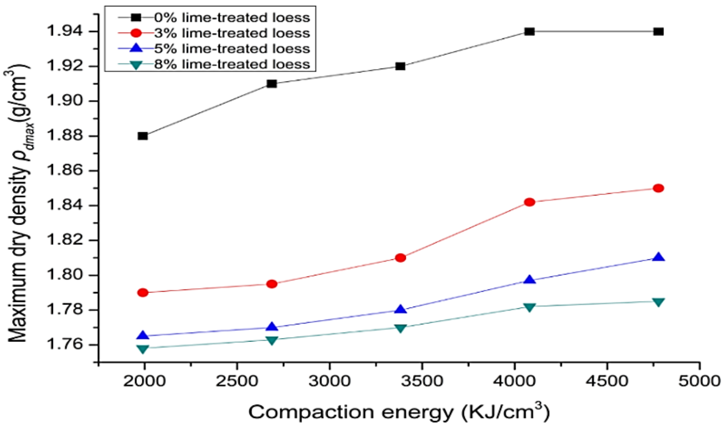

Figure 10. Relation curves of compaction energy and maximum dry density

Figure 9 presents the relation curves of compaction energy and optimum water content w_{opt} under the different compaction energy. Figure 10 presents the compaction curves of compaction energy and maximum dry density ρ_{dmax} under the different compaction energy. As it is shown in Figure 9 and 10, For 0, 3, 5 and 8% lime-treated loess, with the increase of compaction energy (from 1990 KJ/cm^3 to 4777 KJ/cm^3), the optimum water content w_{opt} decreased and the corresponding maximum dry density ρ_{dmax} increased. It is important to note that, for different lime-treated loess, a higher compaction energy results in a higher value of maximum dry density ρ_{dmax} and a lower value of optimum water content w_{opt}.

3.4. Degree of Compaction

During the construction of multi-layer highway embankments, the degree of compaction K is an important parameter which used to control the compaction quality of soil embankments. Only when the designed K value of previous layer have been achieved, the successive layer should be allowed to be compacted. The degree of compaction K can be calculated by:

$$K = \frac{\rho_{in-situ}}{\rho_{dmax}} \times 100\% \tag{1}$$

$$\rho_{in-situ} = \frac{\rho}{1 + 0.01 w_{in-situ}} \tag{2}$$

Where K is degree of compaction (%); $\rho_{in-situ}$ = in situ dry density (g/cm^3); ρ_{dmax} =maximum dry density (g/cm^3); ρ = natural density (g/cm^3); $w_{in-situ}$ = in situ water content (%); The value of ρ_{dmax} is obtained from laboratory compaction test. The value of ρ is obtained from in situ tests by using sand cone method (Figure 11). The test results are shown in Figure 12 and 13.

Figure 11. Sand cone method (a) Sand container and base plate; (b) Digging test hole

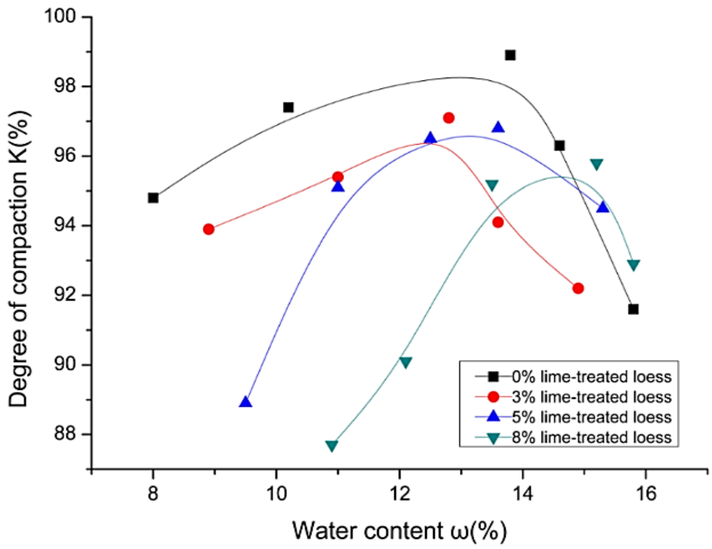

Figure 12. The relation curves of water content *w* and degree of compaction *K*

Figure 12 shows the relation curves of water content w and degree of compaction K for different lime-treated loess under the same in situ compaction procedure. As it shown in Figure 12, for different lime-treated loess, the relation curves of water content w and degree of compaction K exhibit the same shape. With an increase of water content, the value of K increased until it reach the maximum. For 0, 3, 5 and 8% lime-treated loess, the maximum value of K were 98.9, 97.1, 96.8 and 95.8%, respectively. The corresponding optimum water content were 13.8, 12.8, 13.6 and 15.2%, respectively. It can be seen that, the value of K can hardly be achieved 100% in the practical construction of embankments. The increase of lime content induces the decrease of degree compaction K and increases the optimum water content w_{opt}. In order to achieve the optimum compaction quality of lime-treated loess embankments, higher water content and compaction energy is needed during the practical construction of loess embankments.

3.5. Results Comparison (Laboratory Tests and in Situ Tests)

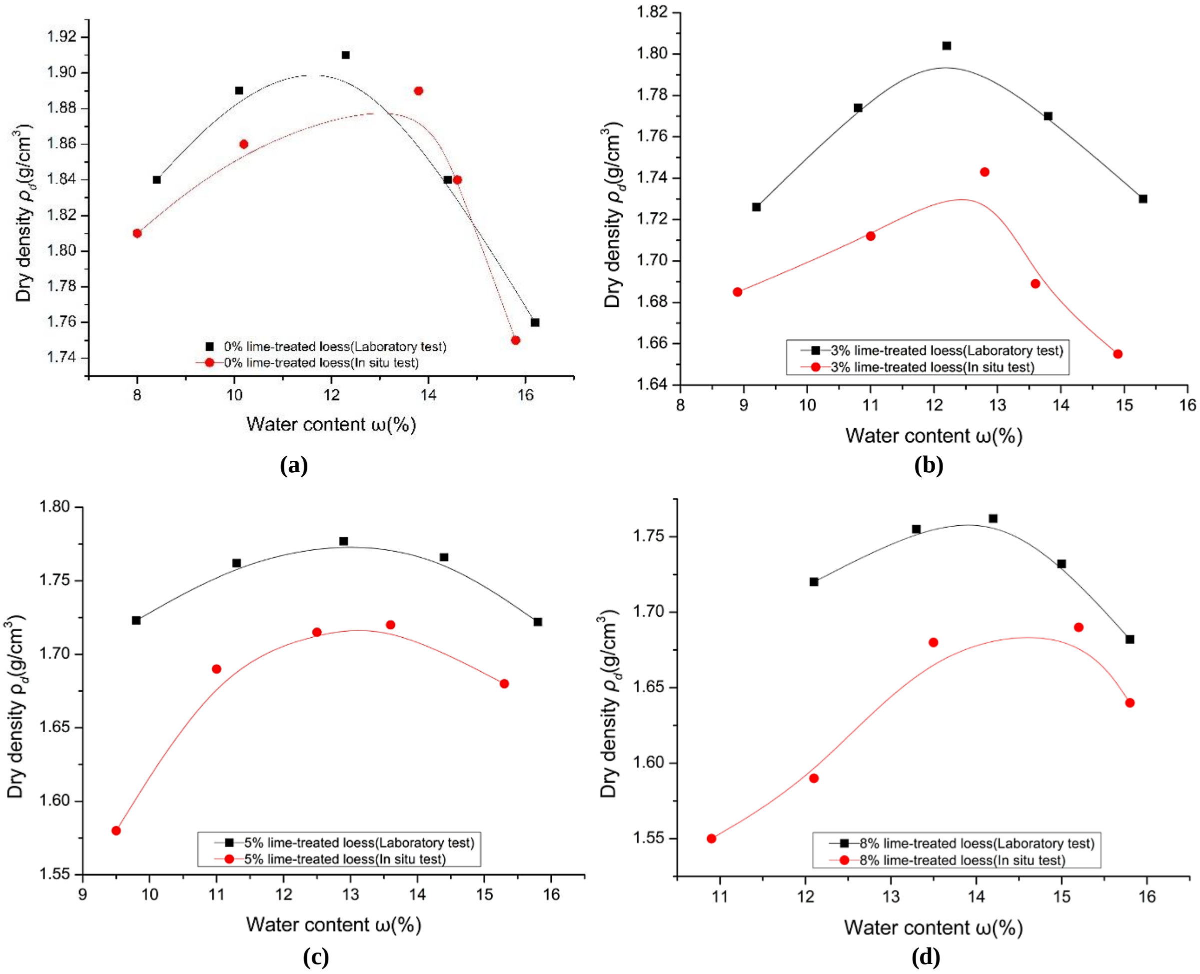

Figure 13. Compaction curves comparison (Laboratory tests and In situ tests) (a) 0% lime-treated loess; (b) 3% lime-treated loess; (c) 5% lime-treated loess; (d) 8% lime-treated loess

Figure 13 presents the comparison of compaction curves obtained from laboratory tests and in situ tests. As it shown in Figure 13, compaction curves from the laboratory and in situ compaction tests at different compaction conditions exhibit nearly the same shapes. For 0, 3, 5 and 8% lime-treated loess, ρ_{dmax} obtained from laboratory compaction tests was 1.91, 1.795, 1.777 and 1.764, respectively. The corresponding w_{opt} was 11.7, 12.2, 12.8 and 13.6%, respectively. Based on the results of in situ tests, for 0, 3, 5, 8% lime-treated loess, the in situ value of $\rho_{in-situ}$ was1.89, 1.743, 1.72 and 1.69, respectively. The corresponding $w_{in-situ}$ was 13.8, 12.8, 13.6 and 15.2%, respectively.

As it can be seen, the in situ value of $\rho_{in-situ}$ was lower than ρ_{dmax} obtained from laboratory tests. However, the corresponding in situ value of w_{dmax} was greater than w_{opt} obtained from laboratory tests. It is also important to note that, the situ value of ρ_{dmax} achieves it's maximum value when in situ water content was larger than the value of optimum water content w_{opt} (+1-2%). During the construction of loess embankments, in order to reach optimum compaction, it is important to keep the value of in situ water content $w_{in-situ}$ is larger than the value of optimum water content w_{opt} (+1-2%).

4. Conclusion

- For different lime-treated loess, with an increase of water content w, dry density ρ_d increases until it reach the maximum value ρ_{dmax}. Once water content exceeds optimum water content $\boldsymbol{w_{opt}}$, dry density ρ_d decreases dramatically.
- The addition of lime induces the increase optimum water content $\boldsymbol{w_{opt}}$ and the decrease of maximum dry density ρ_{dmax}. With the increase of lime content, more water will be needed to obtain the optimum compaction of lime-treated loess.
- With an increase of compaction energy, the maximum dry density ρ_{dmax} decreases and the optimum water content $\boldsymbol{w_{opt}}$ increases. In order to achieve optimum compaction, it is useful to increase compaction energy.
- The value of K can hardly be achieved to 100% in the field construction of embankments. The increase of lime content induces the decrease of degree compaction K and increase the optimum water content $\boldsymbol{w_{opt}}$.
- The situ value of $\rho_{in-situ}$ achieves it's maximum value when in situ water content was larger than the value of optimum water content w_{opt} (+1-2%). In order to achieve the optimum compaction quality of lime-treated loess embankments, higher water content and compaction energy is needed during the practical construction of loess embankments.

5. Acknowledgment

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6. References

[1] Assallay, Rogers, c.d.f, SmalleyI.J. "Formation and collapse of metastable particle packings and open structures in loess deposits". Engineering Geology. 48 (1997) 101-115.

[2] Jefferson I.F, Mavlyanova N, O'hara-dhand K. "The engineering geology of loess ground: 15 tasks for investigators—the Mavlyanov programme of loess research". Engineering Geology. 74 (2004) 33-37.

[3] Ping li, Sai vanapalli, Tonglu li. "Review of collapse triggering mechanism of collapsible soils due to wetting". Journal of Rock Mechanics and Geotechnical Enginee, (2016) 256-274.

[4] Derbyshire E, Mellors T.W. "Geological and geotechnical characteristics of some loess and loessic soils from China and Britain: A comparison". Engineering Geology. 25 (1988) 135-175.

[5] Rogers, c.d.f., Dijkstra T.A, Smalley,I.J. "Hydroconsolidation and subsidence of loess: Studies from China, Russia, North America and Europe: In memory of Jan Sajgalik". Engineering Geology. 37 (1994) 83-113.

[6] Ma F, Yang J, Bai X. "Water sensitivity and microstructure of compacted loess". Transportation Geotechnics. 11 (2017) 41-56.

[7] Yuan Z.X, Wang L.M." Collapsibility and seismic settlement of loess". Engineering Geology. 105 (2009) 119-123.

[8] Sun P, Ling Xu.Ping Sun, Jian-Bing Peng, Li-Wei Chen, Yue-Ping Yin, Shu-Ren Wu. "Weak tensile characteristics of loess in China — An important reason for ground fissure", Engineering Geology 108 (2009) 153–159.

[9] Jiang M, Zhang F, Hu H. "Structural characterization of natural loess and remolded loess under triaxial tests". Engineering Geology. 181 (2014) 249-260.

[10] Liu X, Zhang M, Zhang H. "Physical and mechanical properties of loess discharged from the Yellow River into the Bohai Sea China". Engineering Geology. 227 (2017) 4-11.

[11] Rao S.M, Shivananda P. "Compressibility behaviour of lime-stabilized clay". Geotechnical & Geological Engineering. 23 (2005) 309.

[12]Kavak A, Akyarli A. "A field application for lime stabilization". Environmental Geology. 51 (2007) 987-997.

[13]Sharma N.K, Swain S.K, Sahoo U.C. "Stabilization of a clayey soil with fly ash and lime: a micro level investigation". Geotechnical and Geological Engineering. 30 (2012) 1197-1205.

[14]Cuisinier O, Auriol J.C, Le borgne,T. "Microstructure and hydraulic conductivity of a compacted lime-treated soil". Engineering Geology. 123 (2011) 187-193.

[15]Amadi A.A, Okeiyi A. "Use of quick and hydrated lime in stabilization of lateritic soil: comparative analysis of laboratory data". International Journal of Geo-Engineering. 8 (2017) 3.

[16]Ayeldeen M, Negm A, El-sawwaf M. "Enhancing mechanical behaviors of collapsible soil using two biopolymers". Journal of Rock Mechanics and Geotechnical Engineering. 9 (2017) 329-339.

[17]Frempong E.M. "A comparative assessment of sand and lime stabilization of residual micaceous compressible soils for road construction". Geotechnical & Geological Engineering. 13 (1995) 181-198.

[18]Harichane K, Ghrici M, Kenai S. "Use of natural pozzolana and LIME for stabilization of cohesive soils. Geotechnical and Geological Engineering". 29 (2011) 759-769.

[19]Harichane K, Ghrici M, Kenai S. "Effect of the combination of lime and natural pozzolana on the compaction and strength of soft clayey soils: a preliminary study". Environmental Earth Sciences. 66 (2012) 2197-2205.

[20]Tran T.D, Cui Y.J, Tang A.M. "Effects of lime treatment on the microstructure and hydraulic conductivity of Héricourt clay". Journal of Rock Mechanics and Geotechnical Engineering. 6 (2014) 399-404.

[21]Asgari M.R, Baghebanzadeh dezfuli A, Bayat M. "Experimental study on stabilization of a low plasticity clayey soil with cement/lime". Arabian Journal of Geosciences. 8 (2015) 1439-1452.

[22]Wang Y,Cui Y.J, Tang A.M. "Changes in thermal conductivity, suction and microstructure of a compacted lime-treated silty soil during curing". Engineering Geology. 202 (2016) 114-121.

[23]Krutov V.I, Kovalev A.S. "Soil compaction in industrial building Reconstruction". Soil Mechanics and Foundation Engineering. 23 (1986) 219-223.

[24]Omar M, Shanableh A, Basma A. "Compaction characteristics of granular soils in United Arab Emirates". Geotechnical & Geological Engineering. 21 (2003) 283-295.

[25]Kenai S, Bahar R, Benazzoug M. "Experimental analysis of the effect of some compaction methods on mechanical properties and durability of cement stabilized soil". Journal of Materials Science. 41 (2006) 6956-6964.

[26]G"unaydin,O. "Estimation of soil compaction parameters by using statistical analyses and artificial neural networks". Environmental Geology. 57 (2008) 203.

[27]Fattah M.Y, Al-musawi H.M, Salman F.A. "Treatment of collapsibility of gypseous soils by dynamic compaction". Geotechnical and Geological Engineering. 30 (2012) 1369-1387.

[28]Xia K. "Numerical prediction of soil compaction in geotechnical engineering. Comptes Rendus Mécanique". 342 (2014) 208-219.

[29]Kawai K, Shibata M, Ohtsuki T. "Simulations of static compaction with Soil/Water/Air coupled f.e. analysis", (Springer Berlin Heidelberg, Berlin, Heidelberg, 2012), pp. 181-187.

[30] Mohammed M.M, Roslan H, Firas,S. "Assessment of rapid impact compaction in ground improvement from in-situ testing". Journal of Central South University. 20 (2013) 786-790.

[31] Kim K, Chun S. "Finite element analysis to simulate the effect of impact rollers for estimating the influence depth of soil compaction". KSCE Journal of Civil Engineering. 20 (2016) 2692-2701.

[32] Wang W, Dou,J, Chen J. "Numerical analysis of the soil compaction degree under multi-location tamping". Journal of Shanghai Jiaotong University (Science). 22 (2017) 417-433.

[33] Test Methods of Soils for Highway Engineering, JTG E40-2007, Scientific Research Institute of the Ministry of Communications, P.R.China, 2007.

[34] Field Test Methods of Subgrade and Pavement for Highway Engineering, JTG E60-2008, Scientific Research Institute of the Ministry of Communications, P.R.China, 2007.

[35] Lambe, T.W. "The engineering behavior of compacted clay". ASCE J. Soil Mech. Found. 1958, Div. 84 (SM2) (Proc. No. 1655).

[36] Smith D.L.O, Dick son J.W. "Contributions of vehicle weight and ground pressure to soil compaction". Journal of Agricultural Engineering Research. 46 (1990) 13-29.

[37] Lawton E.C, Fragaszy R.J, Hardcastle J.H. "Stress ratio effects on collapse of compacted clayey sand". J. Geotech, Eng., ASCE 117 (1991) 714-730.

[38] Delage P, Audiguier M, Cui Y, Howat M.D. "Microstructure of a compacted silt". Can. Geotech. J. 3 (1996) 150-158.

[39] Watabe Y, Leroueil S, Le Bihan. "Influence of compaction conditions on pore-size distribution and saturated hydraulic conductivity of a glacial till". Can. Geotech. J. 37 (2000) 1184-1194.

[40] Horpibulsuk S, Katkan W, Apichatvullop A. "An approach for assessment of compaction curves of fine-grained soils at various energies using a one point test". Soils and Foundations. 48 (2008) 115-126.

[41] Jotisankasa A, Coop M, Ridley A. "The mechanical behavior of an unsaturated compacted silty clay". Geotechnique. 59 (2009) 415-428.

[42] Patel S.K, Mani I. "Effect of multiple passes of tractor with varying normal load on subsoil compaction". Journal of Terramechanics. 48 (2011) 277-284.

[43] Shouji Yokohama, Seiichi Miura, Satoshi Matsumura. "Change in the hydromechanical characteristics of embankment material due to compaction state conditions". Soils and Foundations. 54 (2014) 731-747.