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Utilization of high liquid limit soil as subgrade materials with pack-and-cover method in road embankment construction

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Abstract

In order to improve the utilization of high liquid limit soil, the fundamental properties of high liquid limit soil and its direct utilization method are studied in this paper. This work involves both laboratory and fieldwork experiments. The results show that clay and sandy clay both with high liquid limit can be directly used for the road embankment, and the degree of compaction can be controlled at 88 %. The pack-and-cover method in accordance with Chinese technical specifications is recommended to be operated in the engineering practice. The packed height should be less than 8 meters and the total height of embankment no more than 12 meters in the interests of settlement. From the view of stability, the optimal thickness value of top sealing soil layer and edge sealing soil layer is about 1.5 meter respectively, and the geogrid reinforcement spacing should be about 2.0 meters. In addition, based on Yun-Luo expressway in China filled with high liquid limit soil, the construction techniques and key points of quality control in subgrade with pack-and-cover method are compared and discussed in detail, and the feasibility of these schemes are verified by the experimental results.

Keywords: *High liquid limit soil, Direct utilization, Pack-and-cover method, Experimental road, Construction technology.*

1. Introduction

High liquid limit soil is a kind of fine grained soil with two categorial features: (1) more than 90 % of the soil particles have a diameter less than 0.074 mm; (2) the liquid limit is more than 50 %. Accrodding to *Technical Code For Construction Of Highway Subgrades* (JTJ F10-2006, in Chinese)[1]4.1.2, which mentions that "if the liquid limit and plasticity index of the soil is greater than 50 % and 26 respectively, or if the fine grained soil can not be directly compacted, it must not be used in the subgrade directly; until processed by technical measures to meet the design requirements". In order to satisfy the requirements of this technical specification, a lot of research work has been devoted to the amelioration and utilization of high liquid limit soil[2-19]. These researches have created a number of methods for utilizing high liquid limit soil to avoid the losses caused by discarding the soil.

Currently, there are two main methods for utilizing the high liquid limit soil as subgrade filler. One method is mixing kinds of additives into high liquid limit soil to improve the soil's physical and mechanical characteristic, such as "Kangnai" stabilizer [5], "NCS" stabilizer [6], crushed stone [11], gravel [12], rice husk ash [13], phosphogypsum [15], lime [16-18], cement, water glass [19], etc. Crushed stone and gravel in the high liquid soil are being the framework, thus weakening the impact of the fine grained soil on its characteristics and improving the strength and water stability of the high liquid limit soil. Other additives have chemical reaction with high liquid limit soil, which may alter the size composition of the high liquid limit soil, reduce its plasticity index, and increase its strength and water stability. Treated high liquid soil has lower liquid limit and plasticity index and higher CBR, which could be used as a subgrade filler for expressway. Another method is edge covering or core covering treatment [21]. Edge covering treatment is the method in which the center of the subgrade is filled in layers with high liquid limit soil, while both sides of the subgrade are filled in layers with high strength and good water stability. Core covering treatment is the method in which both sides and the top and bottom of the subgrade are sealed with filling of soil with high strength and good water stability.

However, high cost of these improvement schemes has restricted their engineering application.The high liquid limit soil will be more attractive if it can be directly used in subgrade. The main point of this work is to explore the best utilization program of high liquid limit soil. This paper starts from the experimental study on fundamental properties of high liquid limit soil based on Yun-Luo

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Expressway (in China). Then, the method used for direct utilization of high liquid limit soil is presented, and three design parameters of pack-and-cover method are studied further, respectively. Finally, selected sections of the expressway filled with high liquid limit soil are built based on these methods, and the corresponding quality test results are discussed.

2. Characteristics of High Liquid Limit Soil

2.1. Laboratory experiment for high liquid limit soil

The high liquid limit soil samples used in the experiments were obtained from sections (K4+440, K7+480, K18+240, K24+535) of Yun-Luo (Yunfu-Luoding) Expressway from a sampling depth of 2.0m. This study selected four kinds of representative soil samples, and five tests were conducted for each type of soil. The basic physical property indexes are shown in Table 1 and Fig. 1. According to "Test methods of soils for highway engineering (JTG E40-2007)" [18], the soil samples mentioned above can be classified as a kind of high liquid limit clay, a kind of high liquid limit sandy clay, a kind of high liquid limit silt, and a kind of high liquid limit sandy silt.

Table 1 Conventional test results of high liquid limit soil

Soil type	High liquid limit clay	High liquid limit sandy clay	High liquid limit silt	High liquid limit sandy silt
Location	K4+440	K7+480	K18+240	K24+535
Water content (%)	34.1	32.3	34.3	31.6
Optimum water content (%)	20.3	16.2	21.5	15.3
Specific weight	2.71	2.70	2.69	2.69
Density (g/cm^3)	1.86	1.81	1.79	1.88
Dry density (g/cm^3)	1.42	1.4	1.33	1.43
Liquid limit(%)	71.1	64.2	66.1	53.2
Plastic limit(%)	34.9	28.5	39.6	31.8
Void ratio	1.12	0.95	1.07	0.91
Saturation degree(%)	84.6	88.3	89.0	97.2
Compressibility coefficient (MPa^{-1})	0.55	0.42	0.59	0.40

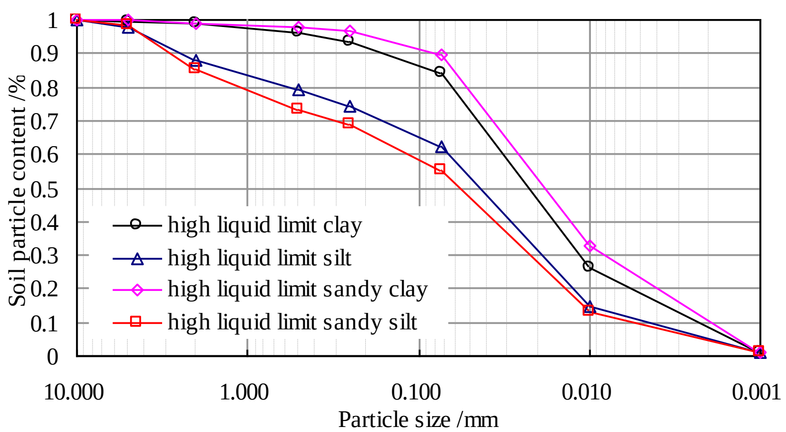

Fig. 1 Sieve analysis results of high liquid limit soil

First of all, laboratory experiments on the four kinds of soil materials were carried out to find out which was suitable for direct utilization. The water content of high liquid limit soil in the area is over 30 %, which is much higher than the optimum water content. Even worse, it is very difficult to reduce the water content to the optimum water content with a error less than 2 % by the air-dry method in a short time. Additionally, it is not easy to make compaction rate to satisfy the standard requirements. If the high liquid limit soil is directly used, the control standard of the compaction rate unavoidably degrades, which must be resolved.

2.2. Experimental analysis on CBR of soil

California bearing ratio (CBR) is one of the most important indices to judge whether the filling can be used as the subgrade or not. If the control standard of the compaction rate degrade, the CBR of the filling which degree of compaction has degraded must be tested. Therefore, the testing experiment is taken first in this work and the results are shown in Table 2.

Table 2 indicates that the CBR of high liquid limit clay and high liquid limit sandy clay are no less than the standard of 3 % when the degree of compaction is reduced by 5%(from 93% to 88%). However, the high liquid limit

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silt and high liquid limit sandy silt can not satisfy the CBR requirement even without reducing the degree of compaction. In other words, only high liquid limit clay and high liquid limit sandy clay may be filled straightly as the degree of compaction are reduced. Before high liquid limit clay and high liquid limit sandy clay used for direct utilization, the settlement and stability are what need to be validated.

Table 2 The CBR values under different degree of compaction

Soil type	Soil sample number (CBR≥3)	Soil sample number (CBR＜3)	Degree of compaction(%)	$CBR_{2.5}$(%)
High liquid limit clay	19	3	88	3.5
			90	4.6
			93	5.6
High liquid limit sandy clay	20	2	88	3.6
			90	5.2
			93	7.2
High liquid limit silt	2	19	88	2.1
			90	2.4
			93	3.1
High liquid limit sandy silt	1	21	88	2.3
			90	2.4
			93	2.9

3. Settlement of High Liquid Limit (Sandy) Clay

The settlement of embankment, which reduces the degree of compaction, needs to be known for the whole research work. Based on lab tests and theoretical analysis, settlement of embankment under different degree of compaction is calculated.

The settlement calculation method is as follows: (1) Take samples on site and conduct the consolidated test on the samples to determine the compressibility coefficient[21]. The degree of compaction of the samples are 88 %, 90 % and 93 %, respectively. (2) Draw the e～p curve according to the results of the tests. (3) Calculate the settlement of embankment using integration method.

The calculation method is demonstrated in detail below[21]: Consider high liquid limit clay as a whole, and the calculation formula is given as:

$$s = a_v pH_2 / (1+e_0) \tag{1}$$

where: s = sedimentation, m or cm, a_v = compressibility coefficient, MPa^{-1}, e_0 = initial void ratio, p = stress, kPa, H_2 = thickness of high liquid limit clay layer, m.

According to the vertical evenly distributed load model of strip-base, the pavement width b is 24.5 m, the slope of road embankment is 1:1.5, the total height of embankment is H, and load calculation diagram is shown in Fig. 2. According to the *Technical Standard of Highway Engineering* (JTG B01-2003, in China) [22], equivalent load on high liquid limit clay layer (Thickness is H_2) can be calculated as p_e ＝25 kPa＋20 kPa＋20 H_1. Here, the first term in the right hand side of the equation is for the load of vehicle, the second one for the load of base course (Thickness is 1m), and the last one for the load of upper layer (Thickness is H_1), respectively. Taking a microprofile from the high liquid limit clay layer as dz along the vertical direction, the load on microprofile according to the principle of vertical static balance is:

$$p_n = bp_e / (b+3z) \tag{2}$$

where: p_n = equivalent load on microprofile, kPa, p_e = equivalent load on high liquid limit clay layer, kPa, b = pavement width, m, z = thickness of microprofile, m.

The dead load from the high liquid limit clay layer above the microprofile is: $\sigma = \gamma \times z$, total load on microprofile is: $p = p_n + \sigma$. The settlement of embankment is:

$$\begin{aligned} s &= \int_0^{H_2} \frac{a_v}{1+e_0} p dz \\ &= \frac{a_v}{1+e_0}\left[\frac{b}{3} p_e\left(\ln(3H_2+b) - \ln b\right) + \frac{1}{2}\gamma H_2{}^2\right] \end{aligned} \tag{3}$$

where: e_0 = initial void ratio, a_v = compressibility coefficient, MPa^{-1}, H_2 = thickness of high liquid limit clay layer, m, b = pavement width, m, γ = gravity of soil, kN/m^3.

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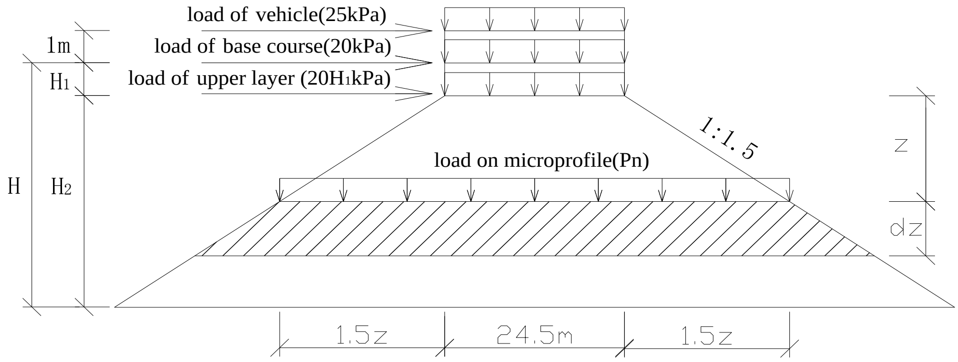

Fig. 2 Schematic diagram of load calculation[13]

The calculation conditions are as follows: the height of embankment is divided into four groups 12.0 m, 10.0 m, 8.0 m, and 6.0 m. As shown in Table 3, ten combinations were defined and used for study. In this paper, high liquid limit clay are chosen to be the samples due to the reclamation capability and performance on CBR test of high liquid limit sandy clay are better than the high liquid limit clay, so if high liquid limit clay can satisfy the requirement, the high liquid limit sandy clay can satisfy too. The results of compression test are presented in Table 4. The results of the gravity test and compaction test are as follows: optimum water content is 20.3%, maximum dry density is 1.68 g/cm^3, specific weight is 2.71. Since the degree of compaction under the embankment no less than 93 % can satisfy the requirement, the results of compression test for the 96 % degree of compaction are given for referrence only.

Table 3 The settlement calculation results of embankment

Case	H(m)	H_1(m)	H_2(m)	p_e (kPa)	Settlement (cm)		
					88%	90%	93%
1	12	2	10	85	30.11	27.66	22.60
2	12	4	8	125	25.62	24.15	19.14
3	12	6	6	165	21.17	19.36	16.21
4	12	8	4	205	16.59	15.52	12.45
5	10	2	8	85	20.24	19.65	15.67
6	10	4	6	125	17.63	16.91	13.41
7	10	6	4	165	14.45	12.02	9.34
8	8	2	6	85	13.04	12.48	9.42
9	8	4	4	125	11.48	9.52	7.40
10	6	2	4	85	7.918	7.03	5.37

Table 4 Laboratory test results of high liquid limit clay

Degree of compaction	Compressibility coefficient (MPa^{-1})	Modulus of compression (MPa)
88%	0.406	5.089
90%	0.358	5.218
93%	0.304	6.431
96%	0.188	10.05

The settlement of embankment could be calculated by Eqs. (1) to (3), and the calculation results are given in Table 3. As seen in Table 3, the change of settlement varies greatly when degree of compaction decreases from 93 % to 90 %, but does not change significant as degree of compaction reduces from 90 % to 88 %. The maximum height of embankment is 12 m, and the maximum thickness of high liquid limit clay layer is 10 m, so the amount of compression of the upper layer filled with non-high liquid limit soil are not taken into consideration.

The result of the calculation shows that, based on case 1, the settlement can reach 30.11cm under the compaction degree of 88 %. Even under the compaction degree of 90 %, the settlement still can reach 27.66 cm. Therefore, to guarantee enough safety margin, the filling height should not be more than 8 m and the whole height of embankment should not be more than 12m(Case 2). According to the Technical code for design and construction of highway embankment on soft ground (JTJ 017-96, in China)[23], it can satisfy the requirement that the settlement after construction in soft soil ground should be no larger than 0.30 m when degree of compaction is reduced to 88 %.

To conclude, high liquid limit clay and high liquid limit sandy clay can be filled directly in embankment using the pack-and-cover method[24] in accordance with the technical specifications in China, and the degree of compaction can be controlled at 88 %. The filling height should be less than 8 m and the total height of embankment should be no more than 12 m.

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4. Stability of High Liquid Limit (Sandy) Clay

Through the previous analysis, high liquid limit (sandy) clay can be filled directly in embankment from the perspective of settlement calculation, and the pack-and-cover method in accordance with Chinese technical specifications is recommended to be operated in the engineering practice. In order to further validate the conclusion, this section will from the perspective of stability calculation, and based on this, study on three design parameters of pack-and-cover method.

The stability calculation method is as follows: (1) Establish a stability calculation model based on the GeoStudio-SLOPE/W module [25,26]. (2) Through laboratory experiments, obtain and input the calculation data. (3) Calculate the stability of embankment using Morgenstern-Price method. (4) Change different design parameters of pack-and-cover method, then calculate the corresponding stability safety coefficient to determine the optimal parameter.

Established stability calculation model and soil parameters of every layer are shown in Fig. 3 and Table 5. Three design parameters of pack-and-cover method are Top(Bottom) layer thickness of sealing soil, Edge layer thickness of sealing soil, and Geogrid reinforcement spacing. The calculate conditions of three design parameters are 0m, 0.5m, 1.0m, 1.5m, 2.0m, 2.5m, and 3.0m. Especially, as a rule of thumb, the bottom layer thickness of sealing soil is 0.5m[27]. In addition, the reinforcement is bidirectional polyester welding geogrid PET60-60, the technical parameters of geogrid are as follows: longitudinal and transverse ultimate tensile strength is greater than or equal to 60 kN/m, longitudinal and transverse tensile strain is less than or equal to 10%, ultimate solder joint peeling force is greater than or equal to 60 N, and breadth is greater than or equal to 4.5m. The surcharge load on top layer of sealing soil is 95 kPa.

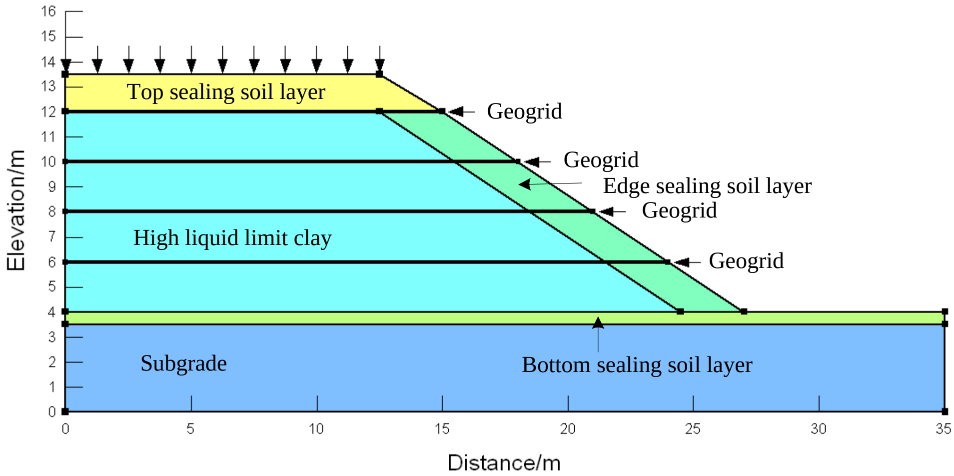

Fig. 3 GeoStudio-SLOPE/W stability calculation model

Table 5 Soil parameters of every layer

Name	Unit weight (kN/m^3)	Cohesion (kPa)	Internal friction angle ($^{\circ}$)
Top sealing soil layer	16300	23	33.7
Bottom sealing soil layer	20000	30	35
Edge sealing soil layer	19200	21.7	31.8
High liquid limit (sandy) clay	18600	17	23.2
Subgrade	23000	24	19

Fig. 4 and Fig. 5 give the calculation results of stability safety coefficients with different design parameters. As seen in Fig. 4, to the top layer of sealing soil, the high liquid limit soil embankment stability safety factor increased firstly and decreased later. Considering the degree of compaction of high liquid limit soil can not reach 96%, so it can not be used in top of embankment. That's mean the less thickness of top layer of sealing soil is 1.5m. Analyzing the embankment stability safety factor and the less thickness of top layer of sealing soil altogether, we can know that the optimal thickness value of top layer of sealing soil is about 1.5m. To the edge layer of sealing soil, the high liquid limit soil embankment stability safety factor comes slight fluctuations, the optimal thickness value of edge layer of sealing soil is about 1.5m. As seen in Fig. 5, to the geogrid reinforcement spacing, stability safety factor declines slightly with the increase of embankments reinforced spacing, so the reinforcement spacing should be about 2.0 m. In addition, the calculation results shows that the safety factor of the stability can reach 2.035, when use the optimal parameters of pack-and-cover method.

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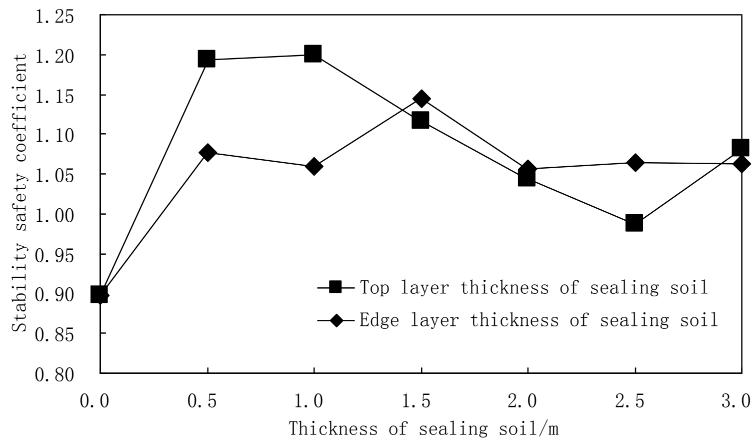

Fig. 4 Stability safety coefficients with different thickness of sealing soil

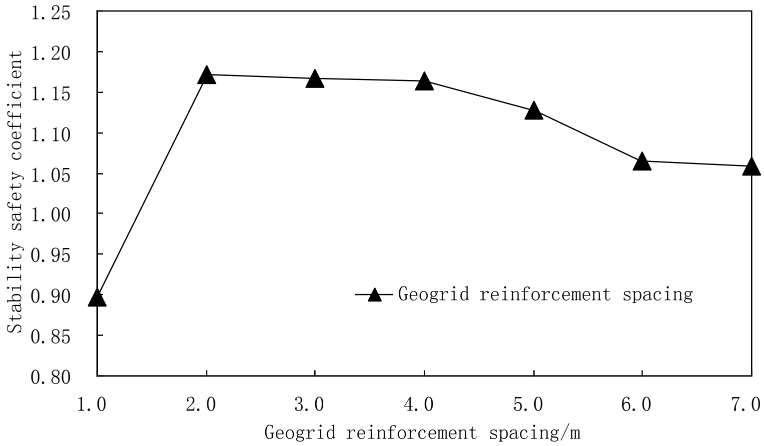

Fig. 5 Stability safety coefficients with different geogrid reinforcement spacing

To conclude, it can significantly improve the safety factor of high liquid limit soil embankment stability by using pack-and-cover method. Three optimal design parameters of pack-and-cover method are Top layer thickness of sealing soil, 1.5m, Edge layer thickness of sealing soil, 1.5m, and Geogrid reinforcement spacing, 2.0m.

5. Fieldwork Along the Yun - Luo Expressway

5.1. Trial of the road section directly utilization with high liquid limit clay

The high liquid limit clay for direct utilization was sampled inform the local section of the road with a roadway station of K4＋425 ~ K4+558, and the physical mechanical indexes of the high liquid limit soil are as follows: The natural water content was 31.5 %, the degree of fine particle was 82.1 %, the liquid limit was 68.9 %, the plastic limit was 34.6 %, the optimum water content was 19.8 %, the maximum dry density was 1.67g/cm^3, the degree of saturation was 91%, the degree of air was 4.4 %, the CBR was 4.2 %, and the compression coefficient was 0.52 MPa^{-1}. Note that the weather is cloudy. The parameters of pack-and-cover method are as follows: Top layer thickness of sealing soil is 1.5m, Edge layer thickness of sealing soil is 1.5m, Geogrid reinforcement spacing is 2.0m.

Based on the testing experiment on the direct utilization of the locality along the road[28-29], the construction technology is summarized as follows:

(1) The spreading thickness of each layer is 35 cm;

(2) The process of the rolling technology follows the steps as: (i) Static pressure one time. (ii) Vibration rolling three times. (iii) Static pressure two times. (iv) Vibration rolling two times. (v) Static pressure three times. The static pressure should be kept on going until the compaction difference between the last two times of vibration rolling less than 0.5 %;

(3) The water content is controlled by airing, and the airing time varies with the change of the water content;

(4) the mass of road roller is 22 ton, the linear load of the road is 704 N/cm, and the times of roller compaction is 6, 8, and 11, respectively.

The final results of the degree of compaction and the degree of air for high liquid limit clay are shown in Table 6. We can generalize from the results that the degree of compaction is greater than 86.5 % when the difference between natural water content and optimum water content is less than or equal to 6 %, and if the degree of air is less than 7.6 %, the degree of compaction can reach 90 %. On the whole, the scheme of direct utilization of high liquid limit clay is feasible and favorable. The recent monitor report, shows the settlement and stability all meet the requirements.

Table 6 Direct utilization results of high liquid limit clay

Times of roller compaction	Road way station	Water content (%)	Dry density (g/cm^3)	Degree of Compaction (%)	Differenceof water content (%)	Degree of air (%)
6	K4＋445	25.6	1.45	86.8	5.8	9.6
	K4＋485	25.2	1.46	87.3	5.4	9.7
	K4＋525	24.4	1.44	86.5	4.6	11.6
8	K4＋485	24.7	1.50	89.7	4.9	7.9
	K4＋525	24.5	1.51	90.3	4.7	7.6
11	K4＋445	24.3	1.51	90.6	4.5	7.6
	K4＋485	24.1	1.54	92.1	4.3	6.4
	K4＋525	24.3	1.52	91.2	4.5	7.0

5.2. Trial of the road section with high liquid limit sandy clay

The high liquid limit sandy clay for direct utilization was collected from the section of the roadway with the station of K7＋462~K7+546, and the physical-mechanical indexes of high liquid limit sandy soil are summarized here: Natural water content was 29.5 %, degree of fine particle was 67.4 %, liquid limit was 67.4 %, plastic limit was 31.2 %, optimum water content was 14.2 %, maximum dry density was 1.91 g/cm^3, CBR was 4.1 %, and maximum difference of water content (when degree of compression was 90%) was 5.7 %. The weather is cloudy and windy. The parameters of pack-and-cover method are as follows: Top layer thickness of sealing soil is 1.5m, Edge layer thickness of sealing soil is 1.5m, Geogrid reinforcement spacing is 2.0m.

Similarly, the construction technology is given below:

(1) The spreading thickness of each layer is 35 cm;

(2) The steps for the rolling process is given here: (i) Static pressure one time. (ii) Micro vibration rolling two times. (iii) Hard vibration rolling two times. (iv) Static pressure one time. (v) Check the degree of compaction. (vi) Hard vibration rolling two times. (vii) Static pressure one time. (viii) Check the degree of compaction. (vi) Hard vibration rolling two times. (x) Static pressure one time. (xi) Check the degree of compaction;

(3) Water content is determined by airing;

(4) The mass of road roller is 18 ton, the linear load is 529 N/cm, and times of roller compaction is 6, 9, and 12, respectively.

Also the final results of degree of compaction and degree of air for high liquid limit sandy clay are shown in Table 7. The results show that the water content was controlled well when the soil is rolled. The degree of compaction reached 91.9 % and 93.1 %, and the difference between natural water content and optimum water content reached 4.9 and 4.3 corresponding to the condition that the soil is rolled to 12 times using an 18 ton/m road roller. On the whole, the scheme of direct utilization of high liquid limit sandy clay is feasible, and the compaction degree fulfills the requirement of 90 % and can even reach 93 % . Note that some can even reach. The degree of air can meet the requirement of being no more than 13 % at the same time. The recent monitor report, shows the settlement and stability all meet the requirements.

Table 7 Direct utilization results of high liquid limit sandy clay

Times of roller compaction	Roadway station	Water content (%)	Dry density (g/cm^3)	Degree of compaction (%)	Difference of water content (%)	Degree of air (%)
6	K7＋480	17.7	1.68	88.2	3.5	6.1
	K7＋520	17.2	1.77	92.4	3.0	4.2
9	K7＋480	17.6	1.76	92.2	3.4	4.1
	K7＋520	17.7	1.79	93.7	3.5	2.3
12	K7＋480	19.1	1.76	91.9	4.9	1.4
	K7＋520	18.5	1.78	93.1	4.3	1.4

6. Conclusions

The fundamental properties of direct utilization with pack-and-cover method for different types of high liquid limit soil materials are studied in this paper. Based on fieldwork of the Yun-Luo expressway filled with high liquid limit soil and the laboratory experiments, some construction techniques and key points of quality control in subgrade construction are proposed:

(1) On the basis of soil properties, the soil could be classified into four categories (high liquid limit clay, high liquid limit sandy clay, high liquid limit silt, and high liquid limit sandy silt). If the soil is a kind of high liquid limit clay or high liquid limit sandy clay, the embankment of expressway can be filled directly using the pack-and-cover method recommended by this paper, and the degree of compaction can be controlled at 88 %. If not, this method would not be suitable.

(2) To meet the requirement of settlement control, the packed height should be less than 8 meters and the total height of embankment no more than 12 meters.

(3) From the view of stability, the optimal thickness value of top sealing soil layer and edge sealing soil layer is about 1.5 meter respectively, and the geogrid reinforcement spacing should be about 2.0 meters.

(4) The suggested values of six important indices (the

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degree of compaction, the packed height, the total height of embankment, the optimal thickness value of top sealing soil layer and edge sealing soil layer, and the geogrid reinforcement spacing) of pack-and-cover method have been given in this paper. If some indices choose different values, the analyses of settlement and stability are needed to be carried out referring to this study.

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