

Research Article

Bearing Behavior of the Fly Ash Deposits on Expressway

Chun-yu Cui ¹, Shu-jian Wang ², Wei Cui ³, and Xiao Zheng ⁴

¹Ph.D. Student, Research Center of Geotechnical and Structural Engineering, Shandong University, Jinan 250061, China

²Senior Engineer, Shandong Luqiao Group Co., Ltd., Jinan, Shandong 250021, China

³Associate Professor, Research Center of Geotechnical and Structural Engineering, Shandong University, Jinan 250061, China

⁴Ph.D. Student, School of Engineering and Technology, China University of Geosciences (Beijing), Beijing 100083, China

Correspondence should be addressed to Shu-jian Wang; 410516550@qq.com

Received 28 March 2019; Revised 5 July 2019; Accepted 10 July 2019; Published 25 July 2019

Academic Editor: Giovanni Biondi

Copyright © 2019 Chun-yu Cui et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

The reinforcement treatment for embankment using the fly ash deposits as the filling material for roadbed was clarified in this paper. Studies have shown that fly ash can be used as the filling material for embankment, but the subgrade bearing capacity from the original fly ash deposits cannot meet the requirements for operating. Fly ash has a good condition to run the dynamic consolidation for meeting the requirements of embankment compaction. The modulus of resilience and the California bearing ratio (CBR) of fly ash is close to that of general filling material for embankment. Fly ash also has the engineering properties of high void ratio and low cohesion. The maximum level of compaction of the fly ash deposits can be 93% and the bear capacity can be about twice over before after the treatment.

1. Introduction

Fly ash is generated during the combustion of coal for energy production with the characteristics of large amount of emissions and wide distribution. Fly ash is generally grey in color and powdery in physical character. However, in China, only 20% of fly ash is utilized as a component of building materials or concrete. The large amount of fly ash that has not been used seriously pollutes the environment. How to make waste fly ash profitable is a subject worth studying.

Ahmaruzzaman [1] found that fly ash has a good potential for use in the construction industry including roadway and pavement utilization. Dungca et al. [2] used dredged soil stabilized with fly ash-based geopolymer for constructing road embankments. Field performance data showed that fly ashes can be effectively used in road construction if fly ashes were treated in the right way [3]. Feng et al. [4] figured out that fly ash has the ability to optimize the pore structure to reduce the harmful pores. Furthermore, studies have listed the advantages of fly ash used as a soil stabilizer along roadways such as light weight, high strength, small compressibility, and good water permeability

compared with fine grained soil [5–7]. On the contrary, there are also a few issues when fly ash is used as the filling material of embankment on expressway. The first issue is that it is hard for formed fly ash to stay in a stable condition and certain water content. The second issue is that fly ash is greatly affected by the capillary water and is easily lost due to the rain water or the internal seepage. Those issues are not conducive for the stability of the embankments and slopes in which the point is how to eliminate the adverse effects as much as possible in the design process.

In China, with the fast development of highways, a large number of high embankments have been constructed [8]. The fly ash deposits are naturally deposited but cannot be directly used in the embankment in highway because they have the characteristics of high compressibility, high water content, low compactness, and low bearing capacity. How to deal with the inevitable material field of fly ash has always been a problem in projects due to the limitation of road selections. There are too many disadvantages in current solutions, such as evacuation and replacement require high standards in time, cost, and area and even high cost in environment.

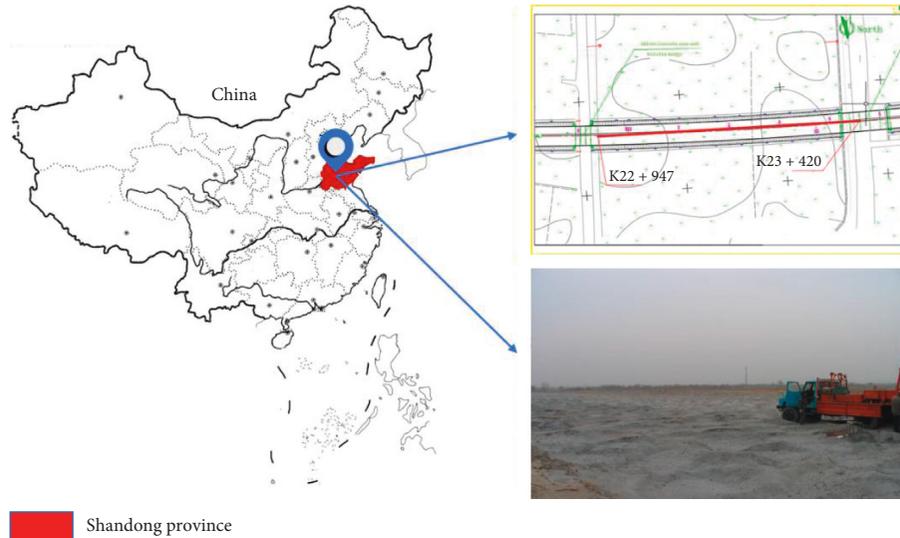


FIGURE 1: The approximate location of K22 + 97~K23 + 420.

Therefore, there is a need to find an effective reinforcement technology for the fly ash deposits to improve the bearing capacity as well as to eliminate the above-mentioned issues.

The research work in this paper was supported by the reinforcement project from the fly ash deposits by means of the laboratory tests and the outdoor tests. The engineering properties of fly ash were captured, and the reinforcement technology of the embankment construction based on fly ash deposits on expressway was analyzed.

2. Project Profile and Geological Conditions of the Field

The area, where the expressway passes is flat, lies in the alluvial plain between the Mount Tai and the lower Yellow River. The surface water in the area mainly comes from surface runoff, ditch, and irrigation. The surface of the area belongs to quaternary loose overburden with a shallow groundwater level; the buried depth in the south of the Yellow River is about 1.5 m to 15 m, about 0.6 m to 7 m in the north. The landform in this area is the typical alluvial plain of the Yellow River, soil layers mainly consist of alluvium, in which sand and clay also exist. The surface is largely composed of clayey silt, mild clay, clay, and fine sand.

K22 + 947~K23 + 420 belongs to the discharge site of fly ash in the fossil-fuel power station, covering 29584 m² and 1.85 × 10⁵ m³ in the storing amount, as shown in Figure 1. The section of fly ash is about 5 m thick and is formed by hydraulic fill with low value in compactness and strength. The original design adopts the scheme of relayering and filling after excavation considering it is hard to compact the fly ash deposits during construction. However, a few problems exist in the scheme: the cost will be high due to the big volume of fly ash; large area is needed after the excavation which will pose environmental pollution; long construction period is also needed depending on the relayering process.

3. Engineering Properties of Fly Ash

The engineering properties of fly ash and bearing capacity of natural foundation need to be determined, to better decide the reinforcement technology aiming at the fly ash deposits. In this paper, laboratory geotechnical test, microcosmic test on fly ash, field loading test, and cone penetration test (CPT) were carried out for the fly ash distributed in the K22 + 947~K23 + 420 section, and the field bearing capacity was comprehensively evaluated.

3.1. Laboratory Geotechnical Test on Fly Ash. Samples of undisturbed and disturbed fly ashes were used in the laboratory test in which all the samples were acquired by the thin wall sampler in the fly ash deposits. The laboratory test is carried out in accordance with the *Test Methods of Soils for Highway Engineering (JTG E40-2007)* [9]. The test contents include moisture content, density, porosity ratio, maximum dry density, optimal moisture content, compression modulus, California bearing ratio (CBR), hydraulic conductivity, adhesive force, and angle of internal friction. The results of laboratory test are shown in Tables 1 and 2. The maximum dry density and the optimal moisture content were determined by heavy-duty proctor compaction test of fly ash, as shown in Figure 2. Meanwhile, a test on modulus of resilience was carried out by using the strength tester of fly ash in optimal moisture content, as shown in Figure 3.

Figure 2 shows that the maximum dry density of fly ash is 1.19 g/cm³ and the optimal moisture content is 29.3%. The maximum dry density of fly ash is obviously smaller compared with the value of cohesive soil and silt in which is 1.5 to 2 g/cm³, and fly ash has a larger value in the optimal moisture content than that of other soil types. Therefore, a strong ability to adapt the rainy seasons of fly ashes can make the drying time shortened when they are used as the filling material in roadbed.

Conclusions can be obtained from Tables 1 and 2 summarized as follows:

TABLE 1: Laboratory test results of fly ash.

Original sample number	Sample depth (m)	Moisture content (%)	Wet density (g/cm ³)	Dry density (g/cm ³)	Proportion	Initial void ratio	Compression modulus E_{S1-2} (MPa)	Permeability coefficient K_{20} (cm/s)	Saturated quick shear test	
									Cohesion (kPa)	Internal friction angle (°)
A1-1	1.0~1.3	33.4	1.38	1.03	2.62	1.562	19.58	$2.38E-4$	12.0	27.8
A1-2	1.7~2.0	42.4	1.31	0.92	2.62	1.881	8.89	—	35.0	26.3
A2-1	1.0~1.3	48.0	1.54	1.03	2.62	1.547	11.44	—	14.0	24.6
A2-2	1.7~2.0	53.7	1.40	0.91	2.62	1.909	6.53	—	1.0	28.6
A2-3	3.0~3.3	61.7	1.41	0.87	2.62	2.039	8.12	$9.32E-4$	0.0	30.5

TABLE 2: Laboratory test results of fly ash.

Maximum dry density (g/cm ³)	Optimal moisture content (%)	Test of CBR			Liquid limit w_L (%)	Plastic limit w_P (%)	Plastic index I_P	Modulus of resilience (MPa)	
		Compactness (%)	Dry density (g/cm ³)	CBR _{2.5} (%)				E_i	E
1.19	29.3	90	1.071	6.9	49.8	30.1	19.7	$E_{50} = 53.8$	51.56
		93	1.107	8.3				$E_{100} = 52.2$	
		95	1.131	8.7				$E_{200} = 51.0$	
		97	1.154	9.7				$E_{400} = 49.2$	

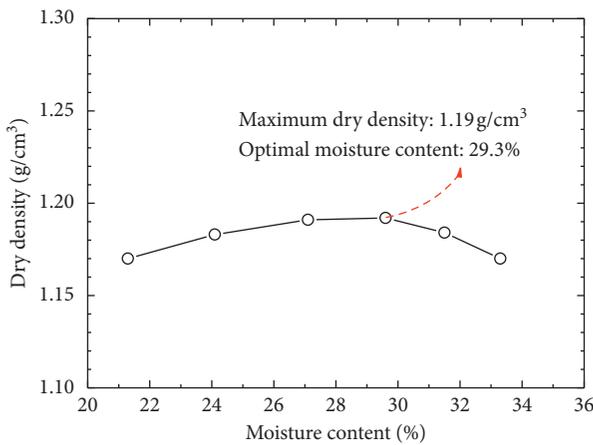


FIGURE 2: Results of heavy compaction test on fly ash.

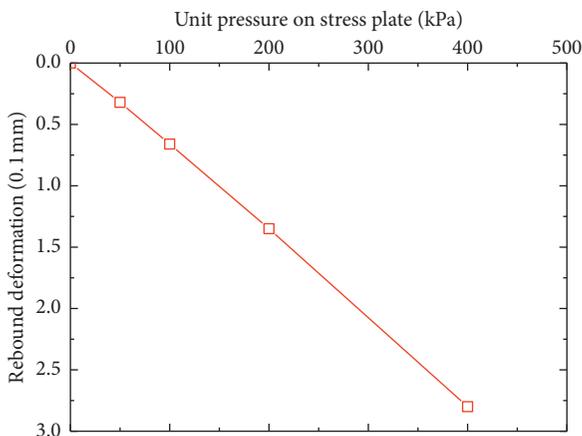


FIGURE 3: Stress-rebound deformation curve of fly ash at maximum dry density.

- (1) The moisture content of fly ash in this testing site is larger than the optimal value, e.g., 29.3%, and increases with increasing depth. The moisture content is above the liquid limit (49.8%) when the depth is more than 3 m.
- (2) The dry density in the site is about 0.87 g/cm³ to 1.03 g/cm³, which means the compactness of the fly ash is about 73% to 86%. The foundation of the undisturbed fly ash needs to be compacted and reinforced according to the standards on the degree of compaction.
- (3) The void ratio of fly ash in the site has a relatively large value and increases with increasing depth.
- (4) The compression modulus of fly ash in the site is relatively low with the compressibility of 0.13 MPa⁻¹ to 0.44 MPa⁻¹, which is medium compressibility, and the middle to lower parts are above the medium compressibility.
- (5) The cohesive value is relatively low, e.g., 0 kPa to 14 kPa, and the internal friction angle is 24.6° to 30.5°, which means fly ash cannot be directly used in roadbed.
- (6) Under the compactness value of 90%, 93%, 95% and 97%, CBR_{2.5} is 6.9%, 8.3%, 8.7% and 9.7%, respectively. The fly ash can meet the requirements of the bearing capacity of the embankment after compacted treatment since the CBR_{2.5} value is between the general value ranges of the filling material, e.g., 5% to 15%.

The requirements in the technical specifications for design and construction for fly ash embankment were met of the grain composition through the gradation test. The specifications require the ratio of particles with particle size

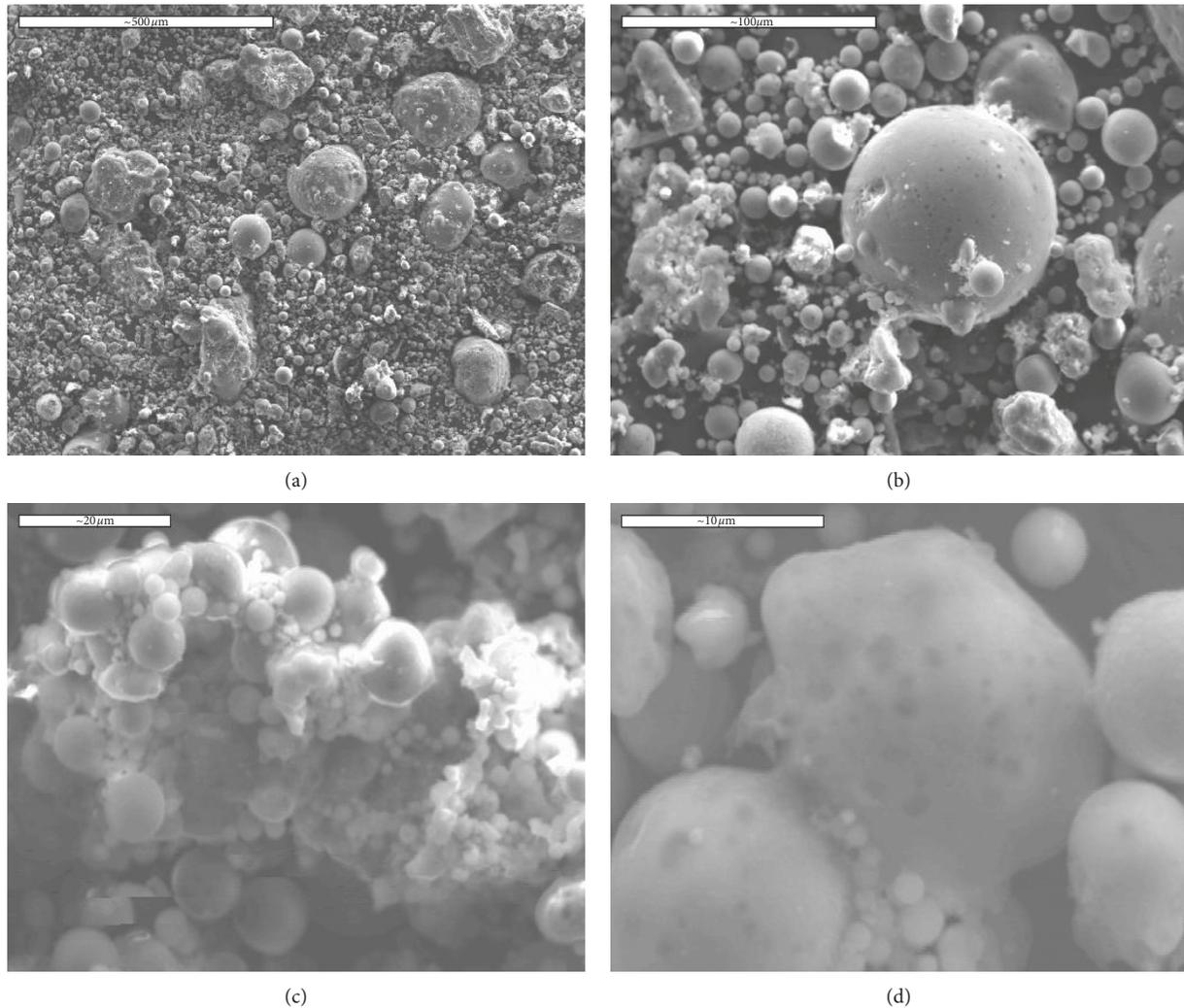


FIGURE 4: Microstructure of fly ash. (a) Precision of 500 μm . (b) Precision of 100 μm . (c) Precision of 20 μm . (d) Precision of 10 μm .

less than 0.075 mm is more than 45% in which the test result was 57.7%.

It can be concluded that the fly ash in the site can be used as the filling material for embankment after processing the reinforcement treatment. Settlement after construction will occur without reinforcement due to high moisture content, low compression modulus, and high discreteness of the fly ash. Fly ash can meet the requirements of the bearing capacity of the embankment after compacted treatment since the modulus of resilience and CBR are close to that in general filling material. Drying time can be shortened because the optimal moisture content is high. Dynamic consolidation is suitable because fly ash has a large void ratio and low cohesion. Partly liquefaction will be caused on the surface of fly ash under dynamic consolidation; then, internal water will be removed through gap inside fly ash.

3.2. Microstructural Test of Fly Ash. To clarify the characteristics on the grain composition of fly ash, microstructural analyses of fly ash using scanning electron microscope (SEM) were carried out, as shown in Figure 4.

Figure 4 shows that the fly ash is composed of small particles united together and has the cohesion. Fine particle is the main constituent of fly ash focusing on 0.002 mm to 0.075 mm, the particle size of fly ashes is relatively uniform and they are all single-grained. Additionally, particles will stay in suspended state under a high moisture content.

3.3. Field Loading Test of Fly Ash. The bearing capacity of the field site needs to be clarified before reinforcement to assess the bearing capacity of the field site after reinforcement. For foundation in expressway, plate loading tests are usually used for determining the subgrade bearing capacity. Therefore, four points were settled in the field test, in which, test point 1 was set at K23 + 010, test point 2 was set at K23 + 130, test point 3 was set at K23 + 250, and test point 4 was set at K23 + 370.

The plate loading test was carried out in a test pit, and a specially made 0.6 m \times 0.6 m thick steel plate was used as the bearing plate. The slow maintained load test method was adopted in the loading test to observe the displacement of the bearing plate by using the dial indicator. The oil jack was

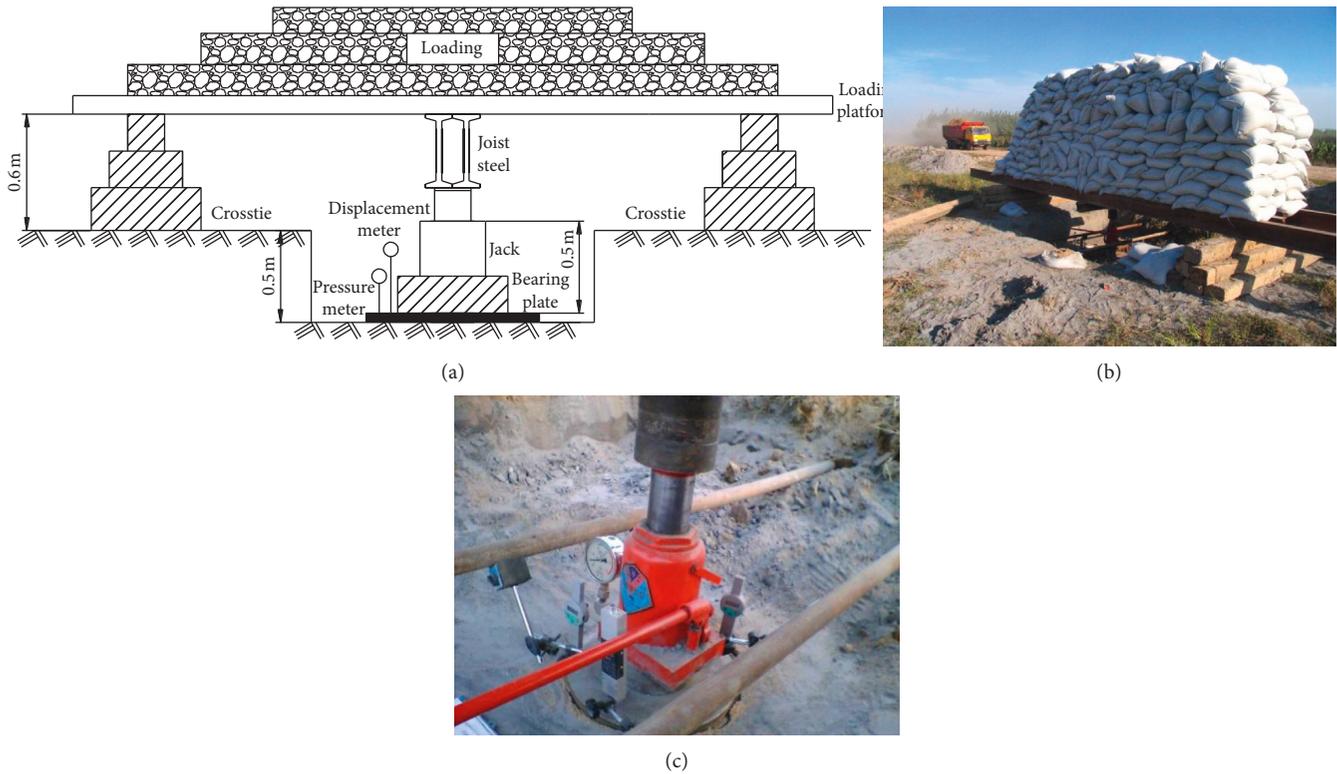


FIGURE 5: Arrangement of plate loading test.

used for pressuring, heavy weight such as sand pocket, and steel ingot was used for loading, as shown in Figure 5.

The stress-deformation curve of four points using plate loading test is shown in Figure 6.

It can be concluded from Figure 6 that the proportional limit of test points 1 to 4 are adopted as 121 kPa, 142 kPa, 100 kPa, and 106 kPa, respectively, and the ultimate bearing capacity of test points 1 to 4 are taken as 253 kPa, 282 kPa, 210 kPa, and 183 kPa, respectively. The bearing capacity of four test points in the field loading test of fly ash are adopted as 154 kPa, 177 kPa, 127.5 kPa, and 125.3 kPa, respectively.

3.4. Static Penetration Test of Fly Ash. The cone penetration test (CPT) on 12 test points was carried out in this paper, and cone resistance q_c and lateral friction f_s were obtained in the test, as shown in Figure 6.

According to the *Editor Committee of Handbook of Engineering Geology* [10], the subgrade bearing capacity f_0 can be calculated using the following equation:

$$f_0 = 36q_c + 44.6. \quad (1)$$

It can be seen from Figure 7 and equation (1) that the subgrade bearing capacity of four test sites, such as K23 + 010, K23 + 130, K23 + 250 and K23 + 370, are computed as 134.2 kPa, 114.8 kPa, 111.6 kPa, and 101.4 kPa, respectively, in which the average value is 115.5 kPa. Therefore, the fly ashes in the testing site cannot be directly used at the roadbed because the operating requirement of subgrade bearing capacity on expressway is not less than

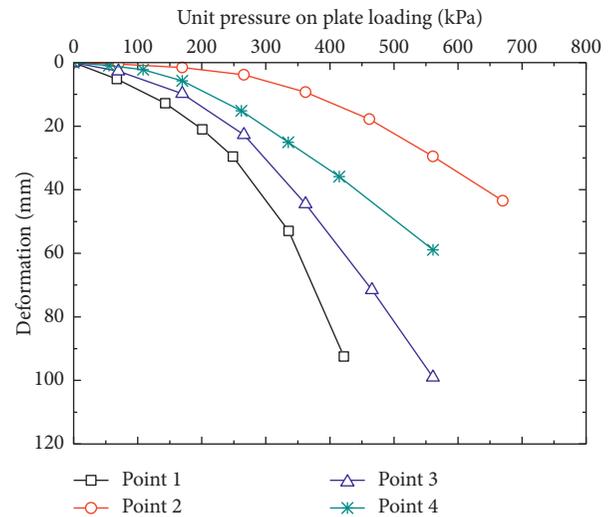


FIGURE 6: Stress-deformation curve of plate loading test.

130 kPa. Reinforcement treatment should be carried out if fly ash is needed for the roadbed.

4. Reinforcement Treatment on Fly Ash Deposits

Treatment methods such as dynamic consolidation and cement injection pile are usually used to improve the bearing capacity of fly ash. K22 + 947~K23 + 420 is a typical fly ash deposit that cannot be directly used for embankment

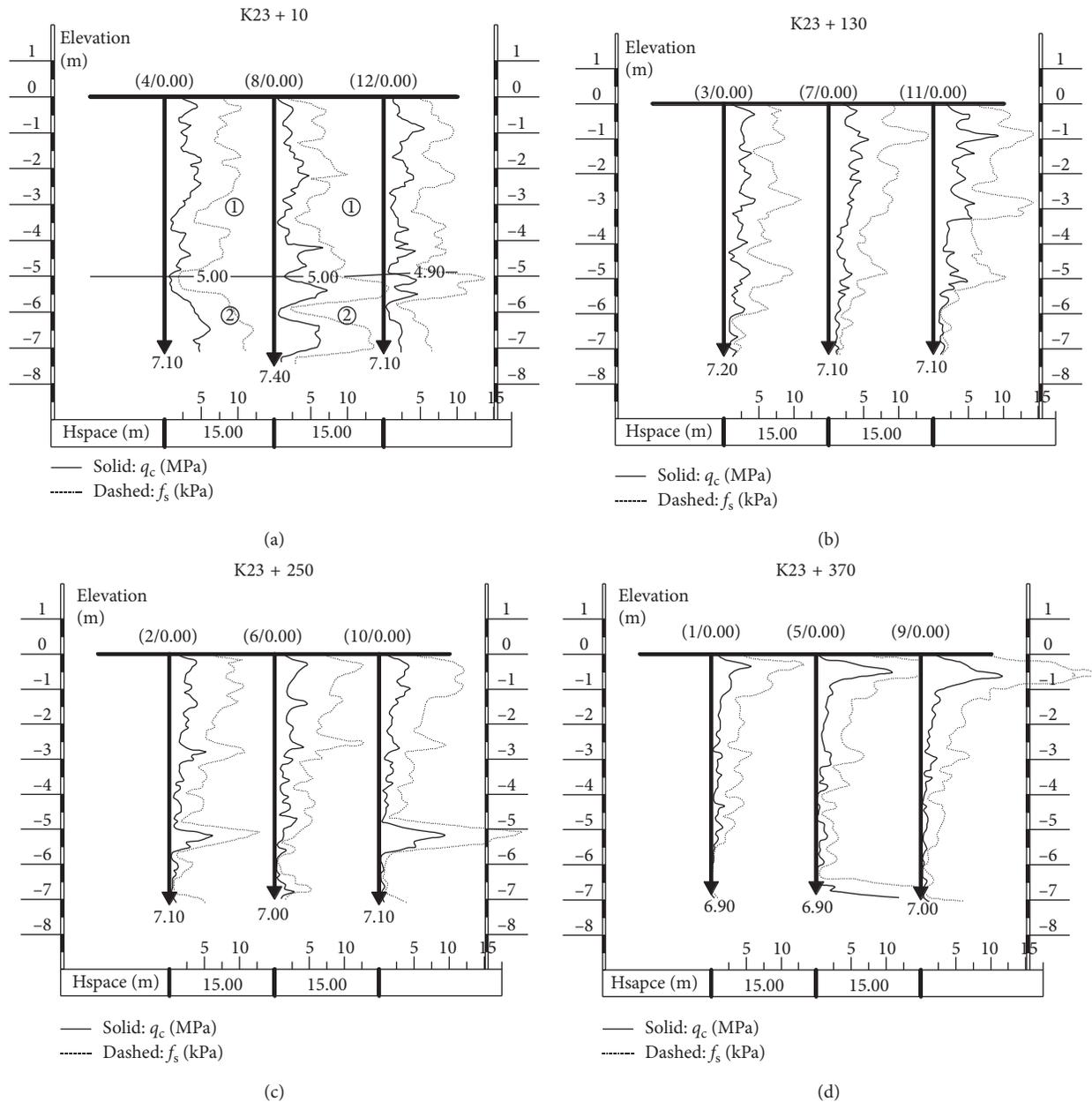


FIGURE 7: Results of CPT.

without reinforcement treatment. The dynamic consolidation method has been widely used in the projects related to foundation treatment due to the following reasons: it can improve the strength and reduce the compressibility of the foundation soil through vibro compaction, dynamic consolidation, and thixotropy effect with low cost and short time [11–14]. Whether the water can be quickly drained from the soil is the key to determine if the reinforcement method can be used to strengthen the foundation or not. Based on the results of Table 1, a good permeability existed in the fly ash of the testing site, which is good for the applications of the dynamic consolidation method because excess pore water pressure is hard to accumulate during the process. As a result, the dynamic consolidation method is decided for the

reinforcement treatment on the fly ash deposits, and the optimum proportion of filling materials on roadbed is also determined through an experimental investigation.

4.1. Field Test on Fly Ash Deposits Using Dynamic Consolidation.

As stated previously, groundwater level is an important factor affecting the dynamic consolidation method. Generally, precipitation should be carried out once the groundwater level is too high in case to ensure the groundwater level is below the proposed reinforcement depth. The thickness of fly ash and groundwater depth in the field site were determined through drilling before the dynamic consolidation, as shown in Table 3.

TABLE 3: Thickness of fly ash and groundwater depth.

Mileage number	Thickness of fly ash (m)	Groundwater depth (m)
K23 + 010	4.6	4.7
K23 + 130	7.6	6.7
K23 + 250	7.1	6.2
K23 + 370	6.7	4.4



FIGURE 8: Site work of dynamic consolidation.

It can be calculated from Table 3 that the average thickness of the fly ash layer is about 6.5 m, and the average groundwater level is 5.5 m below the surface. The designed subgrade height of this section is 4 m. The reinforcement depth of 5 m makes it suitable for the fly ash layer in this site based on a comprehensive consideration.

The tamping pattern and maximum energy requirements using the dynamic consolidation method can be acquired through the empirical formula of reinforcement depth H [15]. One can obtain

$$H = \alpha \sqrt{\frac{W \cdot h}{10}}, \quad (2)$$

where W is the pounder weight; h is the falling distance; and the empirical coefficient α can be adopted as 0.53 according to the Zhang [15].

Based on equation (2), it can be computed as $Wh = 890 \text{ kN}\cdot\text{m}$. Therefore, the dynamic compactor with a maximum tamping energy of $1000 \text{ kN}\cdot\text{m}$ was adopted in the testing site.

The main tamping energy was adopted as $1000 \text{ kN}\cdot\text{m}$ in the testing site, and there was 12 hits for one tamping time. The distance between points of the main tamping was $3.5 \text{ m} \times 3.5 \text{ m}$, and the settlement subjected to the tamping was limited to 5 cm for the last two tampings for controlling the quantities of tamping in each point without uplift or destruction. The full tamping energy was adopted as $600 \text{ kN}\cdot\text{m}$, and there was 2 tampings for one time. Each tamping printing overlapped the 1/4 diameter of the other printings for the full tamping. Both the tamping patterns were arranged in a plumb blossom shape. After the excess pore water pressure was dissipated, the total settlement subjected to tamping will be clarified.

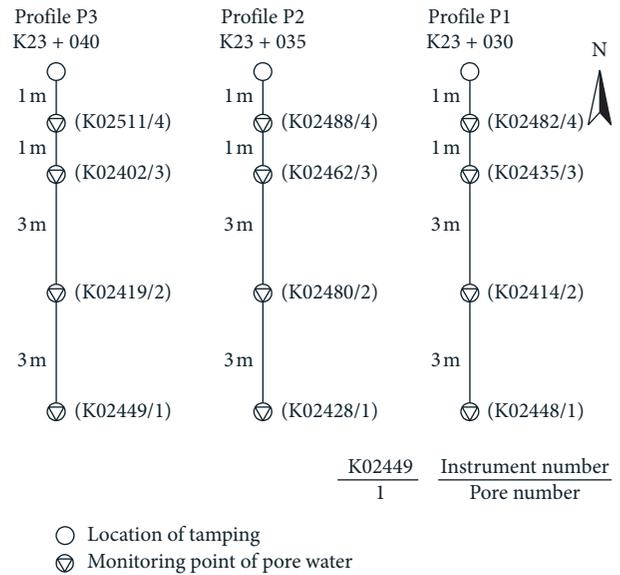


FIGURE 9: Layout of piezometers.

The work site of dynamic consolidation is shown in Figure 8.

4.2. Monitoring of Pore Water Pressure in the Dynamic Consolidation Test. Certain amount of pressure is generated by pore water in the fly ash layer under the vibration caused by tamping. It is necessary to monitoring the pore water pressure in the tamping area according to the *Test Methods of Soils for Highway Engineering (JTG E40-2007)* [9]; thus, the pressure change of pore water in layers can be recorded for the purpose to make sure the construction progress is under control. In addition, the monitoring work is along with the



FIGURE 10: Embedment of piezometers.

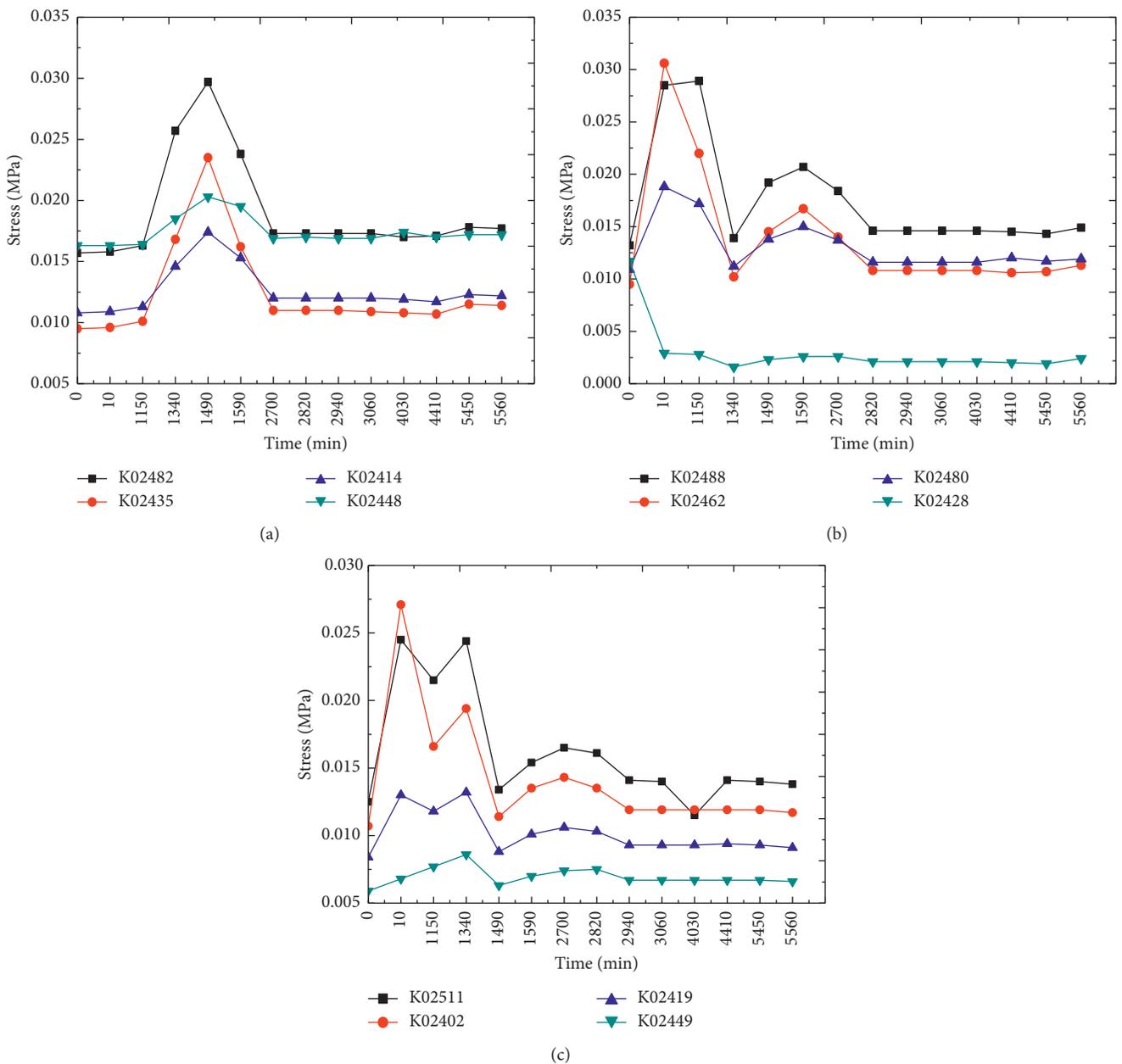


FIGURE 11: Pore pressure of fly ash area before and after dynamic consolidation.

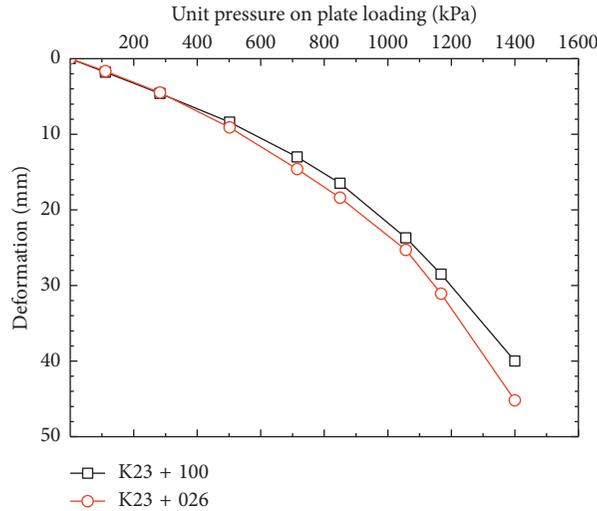


FIGURE 12: Stress-deformation curve of plate loading test on fly ash after dynamic consolidation.

construction, and it stops while the pore water pressure is no longer appears.

Vibrating wire piezometers were selected for the monitoring of water pore pressure, in which the primary precision was 0.1% to 0.2%F·S, and the range was 0.2 MPa to 2.0 MPa. Three monitor stations were set at the area without tamping, three monitor points in each station and one piezometer in each point. 12 piezometers were used in the test; the detailed information of the layout of piezometers is shown in Figure 9 and the embedment of piezometers is shown in Figure 10.

The average value of the measured value after the embedment and 24 hours before the construction was taken as the reference value of the piezometers. After the embedment of piezometers was finished, the frequency of reading the piezometers should be 3 times per day in order to make sure the status and the reference value is under control. Meanwhile, the frequency of reading times can be reduced to one or two per day when the surrounding environment is stable. The water pore pressure before and after the dynamic consolidation is shown in Figure 11.

Figure 11 shows that the pore water pressure reaches the peak value subjected to the tamping, and the pressure value rapidly reduces after the tamping until the value is near 0 in 24 hours. The peak value does not increase with the increasing tamping times but will increase with the decreasing distance between the piezometers and the damping points. In addition, the more the peak value of pore water pressure, the quicker it will reduce after tamping. Results have shown that dynamic consolidation is suitable for the reinforcement of the fly ash deposits, which not only can effectively improve the bearing capacity of the foundation, but also can significantly save the time.

4.3. Effect Analysis on the Fly Ash Deposits Using Dynamic Consolidation. The round plate with diameter of 60 cm was

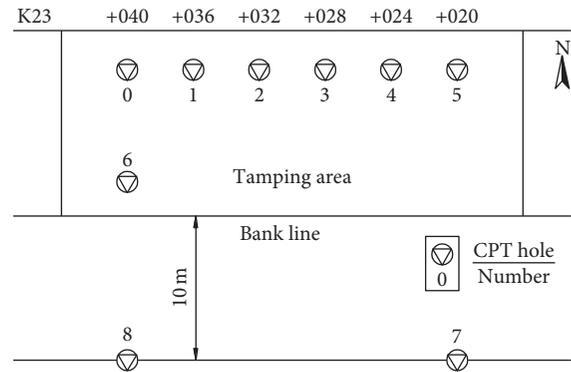


FIGURE 13: Layout of CPT holes after dynamic consolidation.

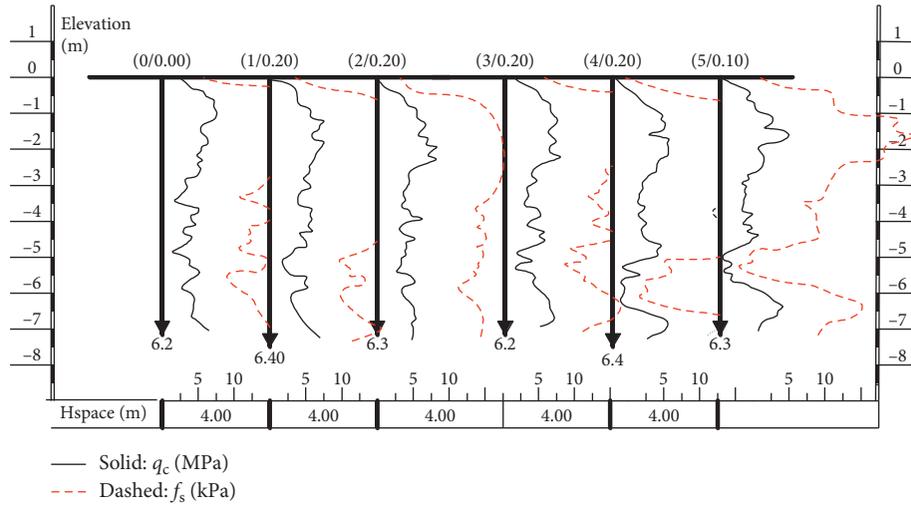
adopted in the plate loading test after the tamping, for the purpose to test the bearing capacity of the foundation. The results are shown in Figure 12.

Based on the plate loading test, Figure 12 shows the proportional limit of K23 + 026 and K23 + 100 are 200 kPa and 220 kPa, respectively; the corresponding ultimate bearing capacity are 880 kPa and 960 kPa, respectively. The bearing capacity of these two locations is 385 kPa and 390 kPa, respectively, which has been greatly improved compared to that before the dynamic consolidation, e.g., 177 kPa. Accordingly, the dynamic consolidation has a great reinforcement effect on the fly ash deposits.

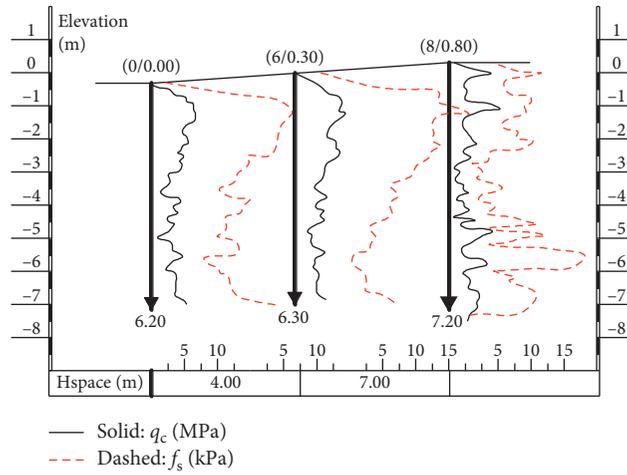
Meanwhile, the cone penetration test (CPT) was carried out between K23 + 020 to K23 + 040, and 9 test holes were set. The layout of the test holes is shown in Figure 13; holes 7 and 8 are the test holes in the natural state.

The results of CPT are shown in Figure 14 and Table 4.

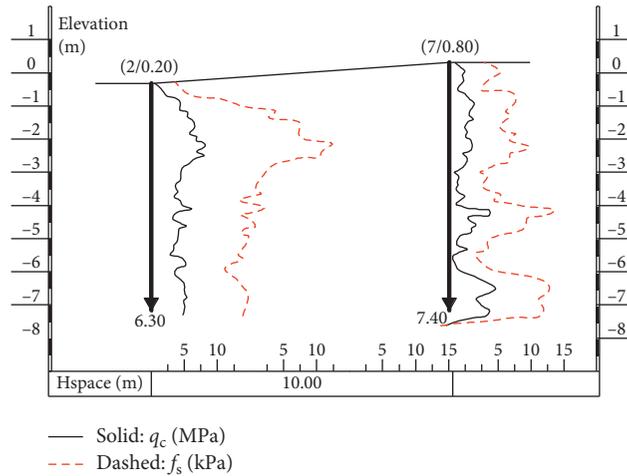
Table 4 shows that the average bearing capacity of foundation in the testing filed is adopted as 192 kPa after the reinforcement treat. The bearing capacity of the testing area (Holes 0–6) is obviously larger than that of the untested area (Holes 7–8). Note that the increasing rate can be 36% in bearing capacity after the dynamic consolidation.



(a)



(b)



(c)

FIGURE 14: Results of CPT on fly ash after dynamic consolidation.

TABLE 4: Results of CPT on fly ash after dynamic consolidation.

Status	Hole	q_c (MPa)	f_s (kPa)	Thickness (m)	Bearing capacity (kPa)
After tamping	0	3.875	135.9	6.2	184.1
	1	4.282	144.8	6.4	198.8
	2	4.291	147.5	6.3	199.0
	3	4.017	136.2	6.2	189.2
	4	3.978	136.1	6.4	187.8
	5	4.215	135.5	6.3	196.3
Native	6	4.054	147.6	6.3	190.5
	7	2.528	81.9	7.4	135.6
	8	2.839	91.7	7.2	146.8

5. Conclusion

This paper presents a reinforcement treatment for embankment using the fly ash deposits as filling material for roadbed. Based on the technical specifications for design and construction for fly ash embankment, fly ash is qualified to be used as the filling material for embankment but lack of certain reinforcement treatment. According to the physical properties of fly ash, dynamic consolidation is put forward as the reinforcement treatment in the field test. The bearing capacity after the dynamic consolidation of the testing area is obviously increased in values, which means dynamic consolidation is suitable for the fly ash deposits in the testing area.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was financially supported by the Shandong Luqiao Group Co., Ltd, Science and Technology Project of Transportation in Shandong Province (2017027b).

References

- [1] M. Ahmaruzzaman, "A review on the utilization of fly ash," *Progress in Energy and Combustion Science*, vol. 36, no. 3, pp. 327–363, 2010.
- [2] J. R. Dungca, W. D. T. Lao, M. Lim, M. D. Lu, and J. C. P. Redelicia, "Vertical permeability of dredged soil stabilized with fly-ash based geopolymer for road embankment," *International Journal of Geomate*, vol. 17, no. 59, pp. 8–14, 2019.
- [3] C.-S. Shon, D. Saylak, and S. K. Mishra, "Combined use of calcium chloride and fly ash in road base stabilization," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2186, no. 1, pp. 120–129, 2010.
- [4] J. J. Feng, J. W. Sun, and P. Y. Yan, "The influence of ground fly ash on cement hydration and mechanical property of mortar," *Advances in Civil Engineering*, vol. 2018, Article ID 4023178, 7 pages, 2018.
- [5] J. S. Qian, *Properties of Fly Ash and Fly Ash Concrete*, Science Press, Beijing, China, 2002, in Chinese.
- [6] H. B. Zhou, H. Li, T. L. Wang, and J. Sun, "Test study on mechanism and behavior of reclaimed soft land improved by high calcium fly ash," *Rock and Soil Mechanics*, vol. 25, no. 5, pp. 783–788, 2004, in Chinese.
- [7] W. Cui, X. Zheng, and Q. Q. Zhang, "Evaluation of bearing capacity of fly-ash highway subgrade based on model test," *Journal of Testing and Evaluation*, vol. 46, no. 3, article 20170034, 2018.
- [8] X. Zheng, Y.-Y. Yang, Q.-Q. Zhang, S.-Q. Wu, and W. Cui, "A novel method for measuring traffic load-induced settlement at different layers of embankment in highway," *Measurement*, vol. 144, pp. 183–191, 2019.
- [9] Research Institute of Highway, Ministry of Transport, *Test Methods of Soils for Highway Engineering (JTG E40-2007)*, China Communications Press, Beijing, China, 2007, in Chinese.
- [10] Editor Committee of Handbook of Engineering Geology, *Handbook of Engineering Geology*, China Architecture and Building Press, Beijing, China, 2007, in Chinese.
- [11] F. H. Zhang, B. T. Wang, H. L. Liu, and Z. H. Zhu, "Application of dynamic compaction to foundation improvement of a flood-prevention dam in Yibin," *Rock and Soil Mechanics*, vol. 25, no. 3, pp. 490–494, 2004, in Chinese.
- [12] J. L. Wang, Y. L. Liu, M. T. Luan, and X. F. Shen, "Testing study of quality detection methods of loess roadbed treated with dynamic compaction method," *Chinese Journal of Rock Mechanics and Engineering*, vol. 23, no. 1, pp. 4562–4567, 2004, in Chinese.
- [13] J. Liu, Y. Luo, G. X. Zhang, Z. L. Dong, and Y. Y. Wang, "Experimental research on saturated mucky foundation treatment with well-point dewatering combined with dynamic compaction method," *Chinese Journal of Rock Mechanics and Engineering*, vol. 28, no. 11, pp. 2222–2227, 2009, in Chinese.
- [14] Q. Q. Zhang, Z. M. Zhang, and H. Q. Wang, "Accident analysis of dynamic compaction in ground improvement of an industrial park in Zhejiang Province," *Chinese Journal of Rock Mechanics and Engineering*, vol. 30, no. 1, pp. 3217–3223, 2011, in Chinese.
- [15] L. J. Zhang, *Design and Construction Technology of Highway Foundation*, China Communications Press, Beijing, China, 2008.



Hindawi

Submit your manuscripts at
www.hindawi.com

