Analysis on the development of chemically-improved soil in railway engineering

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Abstract

Purpose – Explore the development trend of chemically-improved soil in railway engineering.
Design/methodology/approach – In this paper, the technical standards home and abroad were analyzed. Laboratory test, field test and monitoring were carried out.
Findings – The performance design system of the chemically-improved soil should be established.
Originality/value – On the basis of the performance design, the test methods and standards for various properties of chemically-improved soil should be established to evaluate the improvement effect and control the engineering quality.

Keywords Durability, Deformation, Engineering properties, Chemically-improved soil, Performance design, Test method

Paper type Research paper

1. Introduction

Chemically-improved soil has been used for a long time. As early as in the Western Zhou Dynasty, there was the use of chemically-improved soil (Yang, Zhang, Pan, & Zeng, 2009). For more than 100 years, civil engineers have been studying the application of soil to inorganic bond mixtures, such as cement, lime and fly ash. During the Second World War, due to the construction of a large number of temporary roads, the advantages of the convenience of improved soil were vividly manifested, and the application of improved soil was further developed. After the war, with the development of largescale construction, improved soil technology has also been rapidly developed. In the 1940s, chemically-improved soil technology was widely accepted. The American Society for Materials and Testing (ASTM) has compiled the test method of cement-improved soil in the soil test procedure, which provides scientific basis and standard for the popularization and application of chemically-improved soil. So far these methods are still important for the study and evaluation of chemically-improved soil properties.

In China, the chemically-improved soils used in railway engineering include mainly lime improved soils and cement improved soils, which are the focus of this paper. The chemically-improved soils were mainly controlled by strength and compaction coefficient in design and construction. In the severe cold area, the strength of the improved soil was increased in some zones affected by freezing and thawing cycle. The chemically-improved soil in railway

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engineering in China is mainly produced by plant mixing and centralized road mixing (China Railway First Survey and Design Institute Group Co., Ltd., 2017).

There are clear requirements for the strength, deformation and design life of earthwork in the design code of railway earthwork, but there are no relevant standards for deformation and durability of chemically-improved soil. In high-speed railway, the deformation criterion is adopted in earthwork which supports rail structure, the post-construction settlement of subgrade is 15mm and the difference settlement between the transition section and bridge is 5mm. Therefore, deformation and durability indexes are very important for chemically-modified soil similar to artificial materials, especially for high-speed railway. As a result, expansive soil, soft rock and other soil fillers with special properties are seldom improved and used. In the aspects of antifrost heave, waterproof and so on, chemically-improved soil in high-speed railway is rarely used. As construction material, lack of the direct test methods and standards to measure the improvement performance and effect of chemically-improved soil, its use is restricted in railway application. In construction, the quality and reliability of chemically-improved soil is greatly affected by the pulverization degree of original soil, the uniformity of the mixing of amendment agent, the construction efficiency, the compaction quality control and many other aspects. Therefore, the chemical modified filler is not the first choice for construction projects (Chen, Zhang, Yang, Deng, & Wang, 2022).

This paper analyzes the main purpose, function and requirements of chemically-improved soil in railway engineering under different conditions and engineering environment. Based on the analysis of domestic and foreign standards and the test results of chemically-improved soil, some thoughts on the design and construction of chemically-improved soil in railway engineering are put forward.

2. Application technology of chemically-improved soil abroad

2.1 Railway engineering in Japan

In Japan, the chemically-improved soil in railway engineering is mainly divided into lime improved soil and cement improved soil. Strength index is adopted in design. As for the effect of train load, it is considered that the uniaxial compressive strength of it is more than five times of the train load on subgrade surface, which has a certain safety reserve. The trial section construction of cement improved soil is carried out first and the uniaxial compression test is carried out after the treated soil reaches 28 days to determine whether it reaches the prescribed strength. The production generally adopts the way of road mixing. It is required to use machinery that can turn loose, crush, mix and evenly spread. Compaction should choose a roller that is suitable for the character of improved soil and can achieve the specified strength. The overall process, mixing method, construction machinery configuration and quality control of lime improved soil are basically the same as those of cement improved soil (Railway Technical Research Institute, 2013).

2.2 Railway engineering in Germany

In Germany, chemically-improved soil used in railway engineering was divided into three categories: soil improvement, qualified soil improvement and soil consolidation. Soil improvement is a method of improving the gradation and density to facilitate construction. Qualified soil improvement refers to the improvement of soil with certain requirements, such as antifrost and bearing conditions. Soil solidification is a way to increase resistance to traffic and climate stress by adding adhesives. Such treatments can maintain load bearing and freezing resistance for a long time. Deutsche Bahn requires that treatment for long-term purposes should be improved with qualified soil improvement. Qualified soil improvement formulates the minimum amount of binder, the minimum value of the unconfined

compressive strength and the reduction ratio of compressive strength after water immersion. For the soil solidification of SU-ST-GU-GT fillers (similar to the fillers in the subgrade bed of China's railway filling materials), the 28 d unconfined compressive strength is required to be no less than 6MPa and the minimum compaction coefficient of soil solidification is 0.98. The construction of chemically-improved soil is mainly required to meet the design requirements and achieve the purpose of design. When the chemically-improved soil is used as a protective layer, it is required to meet the requirements of the thickness of the protective layer or to ensure the long-term performance of the subgrade. Improvement of weathering rocks and associated fillings requires adequate documentation before use (DB Netzeag AG, 2013).

2.3 United States of America

The American Concrete Institute and the Lime Institute, respectively, have regulations for cement and lime modified soils.

The American Portland Cement Association classifies cement improved soil into four categories: cement-modified soil (CMS), cement-stabilized subgrade (CSS), cement-treated base (CTB) and full depth reclamation (FDR). Major differences are pointed out. The primary materials are fine-grained soil for CMS and CSS and coarse-grained material for CTB. The seven-day compressive strength is generally in the range of 0.7 to 2.1MPa for CSS, 2.1MPa to 4.1MPa for CTB and FDR (Jerod & Wayne, 2020). All the treatments for a zone of cement-modified soil can be completed in one day, instead of the usually more stringent limit of 2–4 hours. After the construction, it can be used as an all-weather working platform (Gregory, Wayne, & William, 2008).

The American Lime Association defined the mix ratio determination and construction technology of lime improved soil based on the role of lime in water absorption, drying, modification and stabilization in soil improvement. The design of lime modified soil in the United States of America is determined by seven steps, the main control indicators are lime content, optimal moisture content and maximum dry density, unconfined compressive strength, water immersion strength and freezing–thawing cycle strength and expansion rate for expansive soil. When used in the design of structural layers, the strength, modulus and volume stability of the solidified soil are generally proposed in combination with the design method. The construction of lime soil in the United States of America usually adopts the road mixing method, which is mixed in situ and then, the heavy vibration roller or sheep foot roller is used for rolling construction and the final surface compaction is completed by the steel wheel roller (National Lime association, 2004).

2.4 Europe earthworks

In Europe the laboratory performance classification specified in this European Standard covers two types of treatment: improvement and stabilization. For improvement, the classification relates to the short-term performance. For stabilization, the classification relates to the medium to long-term performance. It specifies material requirements, mixture properties and test methods, mixture performance classification, field implementation and quality control. For improvement, it classifies and specifies immediate bearing index, moisture condition value and degree of compaction of the modified mixture. When required, the swelling of the mixture shall be examined using either linear swelling or volumetric swelling. For stabilization, due to the consideration of its long-term performance and the stability of its performance, the performance of the mixture and the performance of the compacted sample are classified in detail. It includes the minimum water content, degree of pulverization, immediate bearing index, moisture condition value and degree of compaction standard. The mechanical properties of the mixture of stable chemically-modified soil are generally adopted, such as California bearing ratio, compressive strength, tensile strength, elastic modulus, strength after water immersion, linear expansion rate and volume expansion

rate after water immersion, and the classification is carried out. Freezing resistance and other properties were also suggested. When the intended use and weather conditions require it, the working duration of the solidified soil mixture should be determined. In terms of testing and quality control, key indicators should be specified according to the purpose of improvement and corresponding testing items and indicators should be determined (The British Standards Institution, 2018).

2.5 Comprehensive analysis

The results of classification of chemically-improved soil are shown in Table 1. The classification of chemically-modified soil in the Japan's railway industry is basically the same as that in China. The strength is used to control of design and construction. According to the purpose of soil improvement and the state of soil improvement, the classification criteria of chemically-improved soil are put forward in DB, the United States of America and Europe. Both of them have relatively clear index requirements. Strength is mainly considered in improved soil (modified soil) and deformation and long-term performance indicators are also considered if necessary. Deformation and long-term performance indicators need to be considered in soil consolidation (stabilization).

DB put forward clear technical requirements for chemically-improved soil, and the impact of the environment such as water immersion, freezing and thawing and the requirements of the use site were considered. ASTM has put forward the standard test methods for various properties of chemically-modified soil such as strength, deformation and durability under various conditions. These methods are basically adopted by various industries and specific limits are put forward according to their own requirements. In the European standard, the content is more detailed, which stipulates the classification standard of the performance of chemically-modified soil at different stages, with various indicators, which is convenient for technicians to choose and use. At the same time, it also requires engineers to have a deep understanding of the performance of chemically-modified soil and adopt specific standards according to actual conditions. Generally speaking, the classification of various properties of chemically-modified soil is beneficial to the wide application and quality control of engineering, which is also the development direction and trend of chemically-modified soil for railway engineering in China.

3. Application and analysis of chemically-improved soil test in railway engineering

3.1 Application of chemically-modified soil

3.1.1 Antifrost heave test of chemically-improved soil. In order to study the possibility of using chemically-modified soil in the frozen depth of cold areas, the requirement of frozen-heave

Railway earthworks in China	Railway earthworks in Japan	DB	USA			Europe earthworks
1 Lime modified soil	1 Lime modified soil	1 Soil improvement	1 Lime modified soil	(1)	Drying	1 Improvement
		2 Qualified soil improvement		(2)	Modification	2 Stabilization
				(3)	Stabilization	
2 Cement modified soil	2 Cement modified soil	3 Soil consolidation	2 Cement improved soil	(1)	CMS	
				(2)	CSS	
				(3)	CTB	
				(4)	FDR	

Source(s): Authors' own work

Table 1. Chemically-improved soil classification

ratio of chemically-modified soil not exceeding 0.1% was put forward. The experimental design and field verification of the antifrost heave performance of chemically-modified soil were carried out. According to the test results in Table 2, the filler belongs to sensitive soil for frost heave.

According the Code for Soil Test of Railway Engineering (China Railway First Survey and Design Institute Group Co., Ltd., 2011), the unconfined compressive strength test and frost heave test of the mixture were carried out. According to the maximum dry density and optimal water content of various cement and binder ratios obtained in the compaction test, the specimens for the unconfined compressive strength test were made and the unconfined compressive strength of saturated samples was tested for seven days. The strength of 5% binder content is greater than 1 MPa. The strength of 8% binder content is greater than 2 MPa. The strength of 11% binder content is greater than 5MPa (Zhang, 2017). The test result of frost heaving ratio is shown in Table 3. Through the freezing and thawing cycle test of modified soil, the relationship between the content of binder and the antifrost heave performance of the improved soil is tested. The results show that additive is necessary to achieve the goal of 0.1% frost heaving rate. Under this condition, 5% cement can meet the requirements. Considering the actual climatic conditions in severe cold areas, combined with the results of mass loss rate of samples after saturated freezing and thawing cycle, the mass loss rate of 5% binder content is between 1% and 3%, the mass loss ratio of 8% binder content is no more than 1% and the mass loss ratio of 11% binder content samples is less than 0.7%. Considering the frost heave ratio and mass loss after several freezing and thawing cycle, the mix ratio of 8% cement and additive was selected for the field test.

The surface of the subgrade bed was constructed with 0.60 m of chemically-modified soil. In order to test the antifrost heave performance, a displacement sensor was embedded in the subgrade bed to monitor the frost heave deformation and the monitoring depth was 3.3 m below the surface. According to the displacement-date curve, the surface layer of the improved soil subgrade bed shows the trend of frost heave and melting down. The maximum value of frozen heave is 1.2 mm, as shown in Figure 1, and the value of frozen heave is very small, which has hardly effect on railway operation. Therefore, it is effective to use the frost heave ratio to control the design of chemically-improved soil and subgrade structure.

Table 2. Results of particle analysis tests

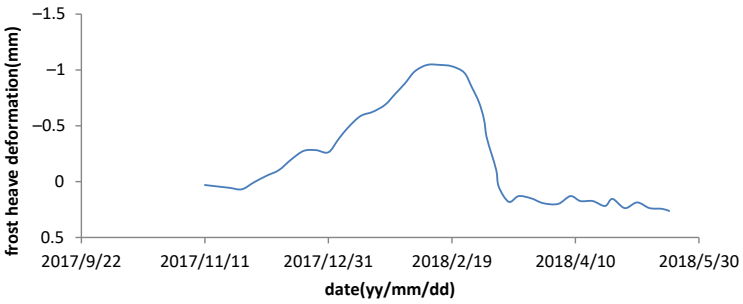
Pore size (mm)	Mass percentage less than the pore size of the total sample (%)
1	99.25
0.5	93.87
0.25	58.86
0.075	24.00

Source(s): Authors' own work

Table 3. Frost heaving ratio (%) of chemically-modified soil with different mixtures

freezing and thawing cycle	1	2	3	4	5	6
5% cement	0.03	0.07	0.17	0.20	0.23	0.30
5% cement + additive	0.02	0.03	0.03	0.05	0.05	0.05
8% cement	0.03	0.03	0.05	0.11	0.19	0.30
8% cement + additive	0.00	0.01	0.01	0.01	0.01	0.01
11% cement	0.01	0.02	0.03	0.05	0.05	0.08
11% cement + additive	0.01	0.01	0.01	0.01	0.02	0.01

Source(s): Authors' own work



Source(s): Authors' own work

Figure 1. Frozen heave deformation curve

3.1.2 High strength chemically-improved soil test in heavy-haul railway. Taking advantage of the high bearing capacity and waterproof performance of the chemically-improved soil, the field test of chemically-improved soil subgrade bed was carried out in the heavy-haul railway trial. The top layer of the subgrade bed was filled with 0.3 m thick graded gravel, under which chemically-improved soil was constructed. Three sections of chemically-improved soil were set. The thickness is 0.3 m, 0.6 m and 0.9 m, respectively. The fine-grained soil included Group C was filled under the improved soil, the liquid limit was 27.7% and the plasticity index was 14.0. The technical requirement of unconfined compressive strength of chemically-modified soil for seven days is not less than 1.5 MPa, and the permeability coefficient is less than 5×10^{-3} cm/s. The laboratory test confirmed the use of fine particle soil for improvement, in which cement content 11%, additives 3% of cement content.

In order to ensure the accuracy of material ratio, uniform mixing and control of large clay particle size during mixing, a screening and crushing funnel was used for the crushing and screening of soil materials and mixing for many times. The screening and mixing were carried out three times in turn with a screening funnel with a gap of 7.5 cm, 5.0 cm and 2.5 cm, respectively, as shown Plate 1. This can not only solve the problem of uneven and large dust of manual spreading amendment but also ensure the accuracy and stability of material ratio

Source(s): Authors' own work

Plate 1. Crushing, screening and mixing of improved soil on site

when mixing, and improve efficiency and can fully solve the problem of excessive particle size (Chen *et al.*, 2022).

Displacement and moisture content monitoring was carried out on site. The moisture content sensor is installed in the graded gravel layer above the chemically-modified soil and the fine-grained soil subgrade under the chemically-modified soil. The deformation of the whole subgrade and the deformation of the fine soil subgrade are monitored. Given that no volume of traffic was generated during the monitoring period after the completion of construction, the total deformation of each structural layer of the subgrade was less than 1 mm. In order to check the physical state and mechanical properties of the chemically-modified soil subgrade after rolling and compaction, ballast and surface graded gravel were removed, the surface of the modified soil was brushed with a brush, the size of the cleaning area was 1 m × 1 m, a small amount of water was sprinkled and no obvious cracks were observed in the field, as shown in Plate 2. The Evd measurement results are shown in Table 4. The observation and test results show that the structural layer of chemically-modified soil subgrade has good mechanical properties under the condition of this mixture ratio (Chen *et al.*, 2022).

The waterproof performance of the chemically-modified soil was mainly analyzed by the monitoring results of the moisture content sensor, which was separately placed in the bottom surface of the 30 cm thick graded gravel layer and the top of fine-grained soil subgrade adjacent to the chemically-modified soil.

The change of water content is shown in Figure 2. During the period of monitoring, there were many obvious rains and the surface water content of the subgrade bed changed significantly, and the monitoring results showed that the volume water content changed by about 35%. The moisture content of the fine-grained soil subgrade has almost no immediate significant change. Only on the whole, it shows a moderate increase with the increase of the upper moisture content, and the change is about 5%. The result shows that the chemically-improved soil layer has a significant separation and anti-seepage performance, and can block the infiltration of a large amount of precipitation. For water-sensitive soil, the use of suitable chemically-improved soil protection can play a better role, but the use of chemically-improved

Source(s): Authors' own work

Plate 2.
Inspection test on site

soil for long-term seepage prevention needs to be cautious. Other sections monitoring show the similar characteristic.

When the chemical-modified soil is required to reach higher mechanical and anti-seepage performance in the subgrade, the strength and permeability coefficient can be used to control the mix ratio of chemical-modified soil. At the same time, the standardized construction technology and equipment of the chemical-modified soil is also the key to ensure the quality of the project.

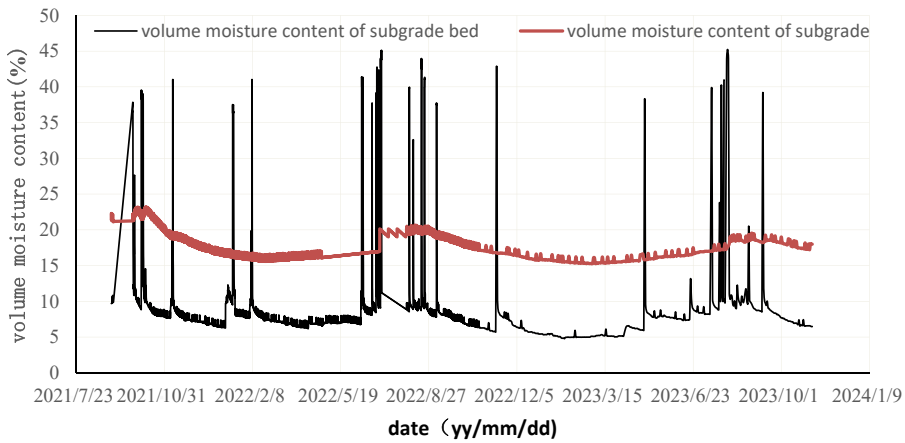
3.1.3 Durability test on chemically-improved soil of mudstone. Mudstone is complex in engineering properties and will slake rapidly when exposed to water after excavation. The main reason is that the mudstone contains expansive minerals such as montmorillonite. Under the condition of dry and wet cycle, the soil structure is destroyed rapidly by the expansion and shrinkage cycles. Therefore, it is rarely used directly as railway filling materials.

Due to the poor engineering properties of mudstone itself, it is still necessary to test the properties of its improved soil after improvement to verify the improvement effect. Compared with silty clay and silty sand chemically-modified soil, the improvement effect test of mudstone chemically-modified soil under dry and wet cycle was carried out (Zhang, Chen, Wang, & Zeng, 2022). The test results show that the expansion and shrinkage of mudstone modified by cement and lime mixed modifier 9% or cement 12% can reach ±0.5% or less in dry and wet cycle, and the overall quality is intact. Other samples with low content of cement or lime modifier lose a lot of quality and some are damaged under dry and wet cycle. Compared with the commonly used cement modified silty clay and cement modified silty

Times	s1(mm)	s2(mm)	s3(mm)	s(mm)	E_{vd}(MN/m^2)	Average(MN/m^2)
1	0.28	0.23	0.24	0.25	89.6	92.3
2	0.22	0.23	0.23	0.23	100.0	
3	0.27	0.24	0.27	0.26	87.2	

Source(s): Authors' own work

Table 4.
E_{vd} test results



Source(s): Authors' own work

Figure 2.
The volume moisture content

sand, the expansion and shrinkage ratio of mudstone modified soil is larger, but it can basically reach a certain stable level and keep the quality and structure intact.

Therefore, for the fillers with poor engineering properties such as easy slake, large expansibility and poor water stability, the durability test under the environment after improvement is of great significance to ensure the engineering quality.

3.2 Application and development analysis of chemically-improved soil in railway engineering

There are two main purposes of chemical improvement soil: one is to improve the properties of soil and rock materials with poor properties, so that they can be used; the second is to enhance the engineering properties of soil and rock materials, so that they can adapt to specific conditions. For traditional railway subgrade, deformation requirements are low. Chemically-improved soil with low content of cement or lime was used. The main purpose is to improve the construction performance of the original filler (such as reducing plasticity index, reducing soil moisture content, etc.) and improve soil strength. Therefore, in the design and construction, the strength, construction moisture content and dry density of the improved soil are mainly considered, so that it can meet the requirements of construction compaction and load bearing. With the construction of high-speed railway, deformation and long-term performance have become the main indexes to measure the performance of subgrade. The change of strength and deformation property of chemically-modified soil under the long-term influence of climate and external force is also more and more important to the subgrade. Therefore, in order to improve the economy and reliability of the use of chemically-modified soil, it is necessary to clarify the performance and technical requirements of the chemically-modified soil in different railway and different environments. Combined with the development of railway construction in China, the application and development of chemically-improved soil are as follows:

(1) To establish the classification standard of chemically-improved soil performance. The design code of railway subgrade puts forward the comprehensive design control standard of strength, deformation and strain for subgrade bed. In order to meet the design requirements of railway subgrade, the comprehensive standard of strength and deformation of chemically-improved soil should be formulated, so that it can be applied to the construction of railway subgrade under different environmental conditions and is beneficial to the cost control of the project. In railway engineering chemically-modified soil can be divided into two categories, one is used for low-speed, special lines and other lines, mainly considering the construction performance of the filled soil and the strength to meet the stability requirements after the subgrade is filled, the other is used for high-speed railway and municipal railway, on the basis of considering the above properties, it should also meet the deformation requirements.

Construction performance is the key to ensure the quality of chemically-modified soil subgrade, including the determination of construction mix ratio, construction technology, the original soil crushing uniformity, mixing uniformity, compactness and allowed construction time, etc. From the point of view of ensuring the construction quality, the construction performance requirements and classification standards should be increased.

(2) Put forward the durability standard of chemically-modified soil. The service life of different structures is different, and the service life of the structure design for the main project has generally reached the level of 100 years. Chemically-modified soil is artificial synthetic material. The engineering properties of modified soil, especially the durability, are different from those of ordinary natural fillers. In the permanent engineering, the durability requirements should be put forward to avoid the degradation of engineering properties and affect the safety and normal use of engineering structures. The durability

index should include the physical state and mechanical performance under the long term, alternating and coupling effects of train load, temperature, humidity, chemical environment and other factors.

(3) Standardize the test methods of various properties of chemically-improved soil and establish evaluation standards. With the progress of technology, the factors mainly affecting the performance of chemically-improved soil are clear. It is possible to establish accurate test method for directly test and evaluating the performance of chemically-improved soil, which is conducive to scientific and reasonable control. For example, silt and sand chemically-modified soil, affected by the nature of the original soil, is difficult to compact to a higher density, but according to experience and mechanical index judgment, its performance can meet the engineering needs, then according to the specific working conditions and the purpose of filler improvement, a reasonable evaluation index can be proposed. The volumetric stability of expansive soil after the improvement of dry and wet cycle, the antifrost heave performance of chemically-improved soil after freeze–thawing cycle in cold areas and the strength and volumetric stability of improved soil under the combined action of dynamic and environmental factors all need direct testing and evaluation criteria.

(4) Establish construction methods and technical requirements for different types of chemically-modified soil. Gravel soil, silt, clay, soft rock and other different types of original soil and their different state, need different soil crushing, mixing equipment, construction technology, construction process and equipment, especially the initial moisture content of soil is the key factor affecting the use of chemically-modified soil, so the construction method and technical standards of different soil types of chemically-modified soil should be established.

4. Conclusions

Through comparative analysis of domestic and foreign standards, laboratory tests and field tests, the conclusions are as follows:

(1) In railway engineering, the deformation index should be increased on the basis of strength, the durability requirement should be put forward and the performance design system of the chemically-improved soil should be established. It is helpful to solve the design and construction problems of chemically-improved soil in engineering and to realize the matching of material classification and structure performance level.

(2) Test methods and standards for various properties of chemically-improved soil are established to evaluate the improvement effect accurately and efficiently and control the engineering quality.

(3) The construction method of chemically-improved soil system is established. The technical requirements of production, construction process and equipment technology of chemically-improved soil are put forward to ensure the production quality and construction quality.

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