Original Research Article

Research on the application of aeolian sand improved soil in the subgrade engineering of the Baotou–Yinchuan high-speed railway

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Abstract: In the field of high-speed railway construction, the stability and durability of subgrade engineering are directly related to train operation safety and passenger comfort. With the advancement of large-scale projects such as the Baotou–Yinchuan High-Speed Railway, the requirements for subgrade materials have become increasingly stringent. Therefore, to effectively improve the construction quality of the subgrade of the Baotou–Yinchuan High-Speed Railway, ensure the efficiency of high-speed railway construction, and lay a foundation for subsequent high-speed railway construction, this paper analyzes and studies the application of aeolian sand improved soil in the subgrade engineering of the Baotou–Yinchuan High-Speed Railway, aiming to provide reference and assistance for relevant practitioners.
Keywords: high-speed railway; Baotou–Yinchuan high-speed railway; subgrade engineering; aeolian sand improved soil; construction quality

1. Introduction

As a natural resource widely distributed in northwestern China, aeolian sand possesses unique physicochemical properties that offer a new material option for subgrade engineering. However, aeolian sand itself has disadvantages such as fine particles, susceptibility to wind erosion, and difficulty in compaction, making it challenging to directly meet engineering requirements when used in subgrade construction. Therefore, improving aeolian sand to enhance its engineering performance has become an important research topic in the field of high-speed railway construction.

2. Analysis of the characteristics of aeolian sand improved soil

2.1. Physicochemical mechanism of aeolian sand

As a unique natural geological material, aeolian sand exhibits both advantages and challenges in the subgrade engineering of high-speed railways due to its physicochemical properties. From a physical perspective, aeolian sand features fine particles and a uniform particle size distribution, with the average particle size mostly ranging between 0.05 mm and 0.5 mm. This characteristic makes it easy to mix evenly with other materials during the improvement process, resulting in a stable improved soil structure. In addition, the loose bulk density of aeolian sand is relatively low, approximately 1.4–1.6 g/cm³, which helps reduce the material consumption during subgrade filling and lower engineering costs. However, the high porosity and low cohesion of aeolian sand also lead to low shear strength, necessitating improvement measures. In terms of chemical properties, aeolian sand is mainly composed of minerals such as quartz and feldspar, which confer high chemical stability and inertness. Nevertheless, aeolian sand often contains certain amounts of soluble salts, such as sodium chloride and sodium sulfate, which can easily dissolve and migrate under the action of moisture, adversely affecting the stability of the subgrade. Therefore, special attention should be paid to the influence of salts during the improvement process, and appropriate measures should be taken to reduce their content or enhance their stability [1].

2.2. Material selection and mix proportion design for improved soil

In the process of material selection and mix proportion design for aeolian sand improved soil, technicians have found through extensive laboratory tests that adding an appropriate amount of cement and fly ash can significantly enhance the strength and stability of aeolian sand. The raw material should be aeolian sand; silt or cohesive soil shall not be used for improvement. If silt or cohesive soil exists in the material source, it shall be stripped off. The subgrade aeolian sand, after sampling and testing as qualified, shall undergo standard compaction and particle density tests. The organic matter content shall not exceed 2%, the silicate content shall not exceed 0.25%, and the plasticity index shall be less than 12.

Specifically, when the cement content reached 8% of the aeolian sand mass, the compressive strength of the improved soil increased by approximately 40%, while the appropriate addition of fly ash (e.g., at a content of 15%) further enhanced its impermeability and durability. This finding not only provides a scientific basis for the selection of improved soil materials but also lays a solid foundation for subsequent mix proportion design. In terms of mix proportion design, technicians adopted the orthogonal experimental design method to systematically investigate the influence of various factors on the performance of the improved soil by setting different levels of cement content, fly ash content, and water–cement ratio. The test results showed that the optimal mix proportions were 8% cement content, 15% fly ash content, and a water–cement ratio of 0.45. Under these proportions, all performance indicators met or exceeded the requirements of subgrade engineering. For example, the compressive strength of the improved soil reached 1.5 MPa, the shear strength increased to 0.3 MPa, and the soil exhibited good water stability and excellent freeze–thaw cycle resistance. This mix proportion design not only optimizes the performance of the improved soil but also reduces construction costs and improves economic benefits.

3. Application analysis of aeolian sand improved soil in the subgrade construction of the Baotou–Yinchuan high-speed railway

3.1. Project introduction

The newly built Baotou–Yinchuan High-Speed Railway main line from Baotou to Huinong South is located within the Inner Mongolia Autonomous Region and the Ningxia Hui Autonomous Region. The eastern starting point of the line is Baotou Station. The line runs westward as a new double track along the Baolan Railway, passing through Baotou City, Bayannur City, Ordos City, Wuhai City in Inner Mongolia, and Huinong District of Shizuishan City in Ningxia. The total length of the main line is 420.25 km, including 17.442 km in the Ningxia section and 402.81 km in the Inner Mongolia section. The main construction work includes 12 subgrade sections (totaling 31.97 km) and 9 double-track mega bridges (totaling 17.006 km), among other tasks. The line starts from Baotou City in Inner Mongolia and passes through the Hetao Plain to Bayannur City. There are numerous tributaries of the Yellow River, and the terrain is slightly undulating, with an average elevation of 1035 m. From Bayannur City to Huinong, the area consists of piedmont alluvial plains. The unaffected Gundal Mountain in Wuhai City is a low-to-medium mountain with undulating terrain, with elevations ranging between 1045 and 1600 m.

This line is located on both sides of the upper reaches of the Yellow River. Surface water along the line mainly comprises the Yellow River and its tributaries. The Yellow River flows year-round with high water flow during rainy seasons, while the tributaries are seasonal rivers. Groundwater along the line mainly consists of Quaternary phreatic water, with minor amounts of bedrock fissure water and karst water in some areas.

Quaternary phreatic water is mainly stored in sandy soils of the Hetao alluvial plain on both banks of the Yellow River, mostly in irrigated areas, with groundwater levels generally buried at depths of 0–1.5 m. Surface water and groundwater along the line are mostly corrosive to concrete, exhibiting sulfate, chloride, and salt crystallization erosion to concrete structures. Soils above the groundwater table, under alternating wetting–drying conditions, salt crystallization damage environments, and chemical erosion environments, are mostly corrosive to railway concrete structures in most sections.

3.2. Raw material collection and pretreatment

In the initial stage of preparing aeolian sand improved soil, raw material collection and pretreatment are critical steps. As the main raw material, the quality of aeolian sand directly affects the subsequent improvement effect and the overall performance of the high-speed railway subgrade. Therefore, during the collection process, geological survey results must be strictly followed to select aeolian sand areas with uniform texture, moderate sand content, and no harmful substance contamination for excavation. In this project, construction personnel used GPS positioning and UAV aerial survey technology to accurately delineate the excavation area, ensuring the quality and quantity of the raw material. The pretreatment stage involves preliminary processing of the collected aeolian sand to remove impurities, adjust particle size distribution, and improve physical properties. Techniques such as screening, washing, and drying are commonly used in this process. For example, vibrating screening machines are used to classify aeolian sand, removing particles that are too large or too small to ensure a reasonable particle size gradation of the improved soil. Meanwhile, washing is used to remove impurities such as soil and plant residues, improving sand purity. Experimental data show that after pretreatment, the silt content of aeolian sand can be reduced to less than 3%, significantly enhancing the subsequent improvement effect. Additionally, moisture content control during pretreatment is also important. Excessively high or low moisture content can affect the mixing uniformity and compactability of the improved soil. Therefore, based on local climatic conditions and construction requirements, methods such as natural drying or mechanical drying are used to adjust the moisture content of aeolian sand to a suitable range. According to engineering practice, the optimal moisture content of aeolian sand is generally controlled between 5% and 8%, at which the mixing effect and compaction performance of the improved soil are optimal [2].

3.3. Mixing and blending technology for improved soil

Mixing and blending technology is one of the key steps in the application of aeolian sand improved soil, as it directly affects the final performance of the improved soil. To ensure the quality of the improved soil with high mixing efficiency and uniformity, construction personnel adopted advanced mixing equipment such as twin-shaft forced mixers. During the mixing process, the mixing time and speed were strictly controlled. Through multiple tests, the optimal mixing parameters were determined: Mixing time of 15 minutes and mixing speed of 30 revolutions per minute. These parameter settings ensure thorough mixing of all components of the improved soil while avoiding particle breakage and performance degradation caused by over-mixing. To verify the effectiveness of the mixing and blending technology, comparative tests were conducted. The test results showed that the uniformity of the improved soil produced with the optimized mixing and blending technology was approximately 20% higher than that produced with traditional methods, and the particle size gradation was more reasonable. This improvement not only enhanced the mechanical properties of the improved soil but also strengthened its water permeability and durability. Furthermore, construction personnel introduced an intelligent monitoring system to perform real-time monitoring and data analysis of the mixing process, ensuring that each batch of improved soil meets the established quality standards. In practical application, because the railway line passes through Inner Mongolia and the Ningxia Hui Autonomous Region, the requirements for subgrade materials are extremely high. The adoption of the improved mixing and blending technology effectively solved the problems of difficult compaction and poor stability of aeolian sand and significantly improved the overall performance of the subgrade. Long-term monitoring and evaluation have shown that the settlement of the improved soil subgrade is far below the design requirements, and no quality issues have occurred, fully verifying the effectiveness and reliability of this technology.

3.4. Analysis of filling compaction technology

To ensure the compaction efficiency of aeolian sand improved soil, construction personnel need to sprinkle an appropriate amount of water on the subgrade after spreading. All spread fill materials must be close to the optimal moisture content to achieve deep moisture penetration. However, this is difficult to achieve in actual construction. Because when water is sprinkled onto the surface of the fill, it penetrates from top to bottom into the lower layers, creating a water-soaked sensation inside the fill under the action of water infiltration. As tested by construction personnel, when the thickness of the fill is 30–60 cm, the optimal moisture content in the lower fill layer is 14.63%, while the moisture content of aeolian sand on the subgrade surface is 19.71%–23.21%. Under such conditions, compaction cannot be carried out immediately. Instead, factors such as the permeation rate of the aeolian sand improved soil, water retention, wind speed along the line, and temperature must be considered. For the watered subgrade fill, construction personnel can accelerate drying by expanding the working area, thereby ensuring that the moisture content of the fill is reduced to an optimal level. To better control the compaction timing of aeolian sand improved soil, construction personnel sampled the aeolian sand improved soil at 20 cm below the subgrade surface for testing, as shown in the figure below.

After watering, the moisture content of the aeolian sand improved soil fill changes significantly within 2 hours, after which it tends to stabilize, eventually approaching the natural moisture content gradually.

Based on the indoor compaction tests conducted by construction personnel, it is found that the optimal moisture content of aeolian sand is approximately 14%. Therefore, to improve compaction quality and control construction costs, construction personnel can perform rolling compaction on the aeolian sand improved soil one hour after watering. The drying time of the fill must be strictly controlled to ensure that compaction is carried out within the prescribed time period, thereby effectively improving subgrade compaction density [3].

3.5. Applicable scope of cement-improved aeolian sand filling

The basic design of the subgrade is as follows: The top width of the subgrade is 13.4 m, with a 4% drainage slope from the center of the subgrade surface to both sides. Due to the lack of qualified fill materials, the bottom layer of the subgrade bed and the embankment below the subgrade bed are filled with aeolian sand mixed with cement as the improved fill. Cement improvement is carried out according to design requirements. The cement used is P.O42.5 slow-setting ordinary Portland cement. The cement content is 5% for the embankment below the subgrade bed, 8% for the bottom layer of the subgrade bed, and a plastic sealing agent is added at 0.6 m below the top surface of the bottom layer of the subgrade bed. The bottom layer of the subgrade bed consists of 1.5 m thick aeolian sand improved soil and 0.8 m thick non-frost-heaving Class A and B fill. The filling height of the subgrade ranges from 6.0 to 6.9 m. The cement-improved aeolian sand is mixed in an aggregate mixing plant and then transported to the site.

In order to determine the optimal number of rolling passes required for the compaction equipment under different loose thicknesses of the improved aeolian sand fill, a test section was selected. Compaction test data were collected for different numbers of rolling passes on each layer of loose fill. The test results were compared to select the optimal loose thickness, construction process, and construction technology control parameters.

4. Inspection standards for cement-improved aeolian sand

Before the construction of cement-improved aeolian sand, representative sections shall be selected for filling process tests based on the properties of the original aeolian sand, the technical parameters of the admixtures, and the optimal mix proportions of the cement-improved aeolian sand. Through these tests, economical and rational construction parameters, such as machinery configuration, mixing, and rolling procedures, shall be determined to guide largescale construction of cement-improved aeolian sand subgrades. At the same time, the transport distance and time shall be established to ensure compliance with the timeinterval limit from completion of mixing of the cement-improved aeolian sand to completion of insitu filling.

The length of the test section shall not be less than 200 m, and the filling test shall be conducted over the full width of the subgrade section where the improved soil is to be placed.

The quality of cement-improved aeolian sand fill shall be controlled in accordance with the filling compaction standards applicable to the corresponding subgrade section, and inspected according to the corresponding indicators.

The quantity and method of quality inspection of cement-improved aeolian sand shall comply with the relevant provisions of the *Standard for Constructional Quality Acceptance of High-speed Railway Earth Structure Engineering* (TB 107512018) and the *Standard for Acceptance of Earthworks in Railway* (TB 104142018).

5. Possible distresses in high-speed railway subgrades using cement-improved aeolian sand and control measures

Possible distresses in high-speed railway subgrades using cement-improved aeolian sand include sand encroachment, wind erosion, insufficient subgrade strength, water stability problems, subgrade deformation, subgrade cracking, subgrade water seepage, subgrade landslide, and subgrade frost heave. The countermeasures include replacing fill material, increasing compaction, installing drainage facilities, adding retaining structures, and setting waterproof layers.

5.1. Control measures

5.1.1. Sand encroachment

During strong wind seasons, sand dunes may reaccumulate on the windward and leeward sides of the subgrade, resulting in sand encroachment. Countermeasures include establishing reasonable protective belts and vegetation belts. Combined measures integrating lowstanding sand barriers (e.g., grid barriers made of inserted live willow branches) and highstanding sand barriers (e.g., fixed highstanding sandtrapping fences) may be adopted. Lowstanding barriers stabilise the sand on the dune surface, while highstanding barriers effectively block windblown sand.

5.1.2. Wind erosion

The slopes of aeolian sand subgrades are susceptible to wind erosion. To mitigate wind erosion, the embankment side slope ratio may be designed as 1:1.5 to 1:2. Depending on the embankment height, both sides of the embankment slope may be protected by hollow bricks with grass seeding and shrub planting between them, or by herringbone waterretaining framework with hollow bricks, grass seeding, and shrub planting. The shoulder may be protected with C25 concrete. For cuttings, an open type with gentle side slopes should be adopted; the side slope ratio of the cut shall be determined based on the cut depth, wind force, wind direction, roadside topography, and protection measures. A sandaccumulating platform shall be provided at the toe of the slope of deep cuttings, and the slopes on both sides of the cutting shall be protected accordingly.

5.1.3. Insufficient subgrade strength

Aeolian sand particles are rounded and have low cohesion, which may lead to insufficient overall stability and strength of the subgrade. During construction, compaction needs to be ensured. For example, using water as a binder, a bulldozer combined with a doubledrum vibratory roller can be used for compaction, allowing the sand particles to rearrange and increasing the internal friction angle to improve shear strength. Where possible, wellgraded coarsegrained soils, such as gravelly soils and sandy soils, should be selected as fillers. If conditions impose constraints and quarry stones nearby must be used as subgrade fill, it shall be ensured that the minimum strength and compaction requirements for the filler are satisfied.

5.1.4. Water stability problems

Although aeolian sand has good permeability, it may still be affected by water in some cases. Effective drainage measures are important, such as installing complete interception ditches, blind drains, and inclined drainage holes, to intercept and drain surface water and groundwater, thus avoiding adverse effects of water on the subgrade.

6. Conclusion

In summary, the innovative application of aeolian sand improved soil in the subgrade engineering of the Baotou–Yinchuan High-Speed Railway not only addresses the shortage of traditional subgrade materials but also enhances the overall performance of the subgrade engineering, bearing significant research importance and substantial application value. In the future, with continuous technological advancements and deeper research, aeolian sand improved soil is expected to be widely applied in more fields, making greater contributions to the development of high-speed railway construction.

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