



Study on Key Technologies of Layered Filling Subgrade with Shield Drilling Sludge

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Abstract. With the rapid development of urban rail transit and tunnel engineering, the output of shield drilling sludge is increasing year by year, posing urgent challenges for waste disposal and resource sustainability. The resource utilization of shield drilling sludge as subgrade filling material offers dual benefits of solving environmental pollution from sludge stacking and reducing reliance on traditional filling materials. However, existing research lacks targeted technical systems for applying shield drilling sludge—characterized by high moisture content, fine particle size, and poor stability—to layered subgrade filling. Moreover, the integration of pretreatment, compaction, and quality control technologies for this specific waste material remains underdeveloped. This study systematically investigates the key technologies of layered filling subgrade with shield drilling sludge. First, the physical and mechanical properties of the sludge (particle size distribution, moisture content, compaction characteristics, shear strength) are analyzed; then, core technologies including sludge pretreatment, layered compaction, and quality control are optimized; finally, field tests are conducted to verify the engineering effect. Results show that after pretreatment (natural drying + mechanical dehydration + 6% lime modification + screening) and scientific layered compaction (25cm layer thickness, 20t vibratory roller, "static-vibratory-static" process), the sludge meets subgrade filling requirements. The filled subgrade exhibits compaction degree ($\geq 93.5\%$), bearing capacity (dynamic cone penetration resistance $\geq 185\text{kPa}$), and stability (total settlement 8-12mm) that comply with design standards, with no significant environmental impact. This study fills the technical gap in targeted application of shield drilling sludge to subgrade engineering and provides a feasible technical framework for its resource utilization, contributing to sustainable construction practices.

Keywords: Shield drilling sludge; Layered filling; Pretreatment modification; Compaction quality; Resource utilization

1 Introduction

In recent years, shield tunneling technology has been widely used in subway, highway, and railway tunnel construction due to its high efficiency, safety, and minimal environmental disturbance [1-2]. However, this process generates massive shield drilling sludge—a mixed waste composed of soil, rock debris, water, and additives [3]. Direct stacking or disposal of this sludge occupies land resources and causes soil/water pollution, restricting sustainable engineering development [4]. Meanwhile, subgrade engineering requires large quantities of filling materials, and the shortage of natural resources (gravel, sand, cohesive soil) and stricter environmental regulations have increased the cost and scarcity pressure of traditional materials [5-6]. Thus, developing low-cost, environmentally friendly alternative filling materials has become a critical research focus in subgrade engineering.

Shield drilling sludge, as a potential recyclable waste, has attracted attention for subgrade filling. However, its complex physical and mechanical properties (high moisture content, fine particle size, poor compaction performance) lead to technical bottlenecks such as low bearing capacity and poor stability in practical application [7-8]. Existing soil stabilization technologies (e.g., lime modification for fine-grained soils) are well-established [9-10], but they lack targeted optimization for shield drilling sludge's unique characteristics. Most prior studies focus on general waste utilization or soil stabilization, failing to integrate pretreatment, compaction, and quality control into a systematic technical system for layered subgrade filling with this specific sludge. Additionally, the engineering feasibility and long-term performance of such applications remain insufficiently verified through field tests.

To address these research gaps, this study aims to: (1) Clarify the adaptability of shield drilling sludge to subgrade filling by analyzing its physical and mechanical properties; (2) Develop a targeted technical system integrating pretreatment, layered compaction, and quality control for the sludge; (3) Verify the engineering effect and environmental sustainability of the proposed technologies through field tests. The hypothesis is that through optimized pretreatment and compaction technologies, shield drilling sludge can be transformed into qualified subgrade filling material, achieving resource utilization while meeting engineering and environmental requirements. This research provides technical support for solving shield sludge disposal problems and promoting sustainable development in transportation infrastructure construction.

2 Physical and Mechanical Properties of Shield Drilling Sludge

The physical and mechanical properties of shield drilling sludge are the foundation for its subgrade application. Due to variations in tunnel projects, stratum conditions, and construction processes, sludge properties differ significantly [11]. Thus, laboratory tests were conducted to analyze the sludge used in this study before engineering application.

2.1 Test Materials and Methods

The shield drilling sludge was collected from a subway tunnel construction site in a city, presenting as blackish-brown, viscous, and slightly odorous. Test samples were prepared following relevant specifications, and physical and mechanical property tests were performed in the laboratory, including particle size analysis, moisture content test, compaction test, and direct shear test. Test methods referred to <Standard for Geotechnical Test Methods>(GB/T 50123-2019) and <Specifications for Design and Construction of Highway Subgrades>(JTG/T 3610-2019).

2.2 Analysis of Test Results

2.2.1 Particle Size Distribution.

Particle size distribution directly affects compaction performance and shear strength. Test results indicate that the sludge is dominated by fine particles: clay particles ($<0.005\text{mm}$) account for 35.2%, silt particles ($0.005\text{-}0.075\text{mm}$) for 42.8%, sand particles ($0.075\text{-}2\text{mm}$) for 22.0%, and gravel particles ($\geq 2\text{mm}$) for less than 1%. This fine-grained composition leads to poor permeability and significant deformation when wet, which is a key challenge for direct subgrade filling—requiring targeted pretreatment to improve gradation and permeability.

2.2.2 Moisture Content.

Moisture content is critical for compaction effect. The natural moisture content of the sludge is 38.5%, with a plastic limit of 22.3% and liquid limit of 45.6%, resulting in a plasticity index of 23.3 (classified as high-plastic clay). The natural moisture content exceeds the optimal range for compaction, leading to poor compaction efficiency and low dry density. Thus, dehydration pretreatment is essential to adjust the moisture content to a suitable level for filling.

2.2.3 Compaction Characteristics.

Compaction tests determine the optimal moisture content and maximum dry density, providing a basis for construction. The test results show the sludge's optimal moisture content is 28.6% and maximum dry density is 1.62g/cm^3 . When moisture content deviates from the optimal value, compaction effect deteriorates significantly: excessive moisture traps air and causes particle slippage, while insufficient moisture reduces particle cohesion. This indicates that strict moisture content control during construction is necessary to ensure compaction quality.

2.2.4 Shear Strength.

Shear strength reflects subgrade stability. Direct shear tests under different compaction degrees show that cohesive force (c) and internal friction angle (φ) increase with compaction degree. At 93% compaction (meeting subgrade requirements), $c=28.5\text{kPa}$ and $\varphi=18.6^\circ$; at 95% compaction, $c=32.8\text{kPa}$ and $\varphi=20.3^\circ$. This demonstrates that

improving compaction degree effectively enhances shear strength, emphasizing the importance of optimizing compaction technology to ensure subgrade stability.

3 Key Technologies of Layered Filling Subgrade with Shield Drilling Sludge

Based on the sludge's physical and mechanical properties and subgrade engineering requirements, the key technologies for layered filling include sludge pretreatment, layered compaction, and quality control—optimized to address the sludge's unique characteristics and fill the technical gap of targeted application.

3.1 Sludge Pretreatment Technology

Natural shield drilling sludge (high moisture content, high viscosity, poor stability) cannot be directly used for filling. Pretreatment aims to improve its physical and mechanical properties, with core technologies including dehydration, modification, and screening.

3.1.1 Dehydration Treatment.

Dehydration reduces moisture content to the optimal range for compaction. Common methods include natural drying (low cost, weather-dependent), mechanical dehydration (high efficiency, high equipment investment), and chemical dehydration (suitable for high-viscosity sludge). Combining natural drying and mechanical dehydration was selected for this study, balancing efficiency and cost: sludge is first air-dried for 3-5 days (moisture content reduced to ~35%), then mechanically dehydrated using a plate and frame filter press to reach 26-30% (optimal range). This two-step process avoids the limitations of single methods (e.g., weather dependence or high cost) and ensures stable dehydration effect.

3.1.2 Modification Treatment.

To further improve mechanical properties, modified sludge was treated with modifiers (cement, lime, fly ash). Lime was chosen for its cost-effectiveness and proven effectiveness in stabilizing fine-grained soils^[12-13]. Tests show that adding 5-8% lime significantly improves sludge performance: at 6% lime content, optimal moisture content is 27.8%, maximum dry density 1.68g/cm³, $c=35.2\text{kPa}$, and $\phi=21.5\%$ —superior to unmodified sludge. Lime reacts with clay minerals to form cementitious substances, enhancing cohesion and shear strength, while improving particle aggregation and compaction performance. This targeted modification addresses the sludge's poor stability and fills the gap of optimized modifier dosage for shield drilling sludge.

3.1.3 Screening Treatment.

After dehydration and modification, the sludge may contain large particles/impurities that affect compaction uniformity. A 2cm mesh screen is used to remove these, ensuring filling particle size meets subgrade requirements. This step complements dehydration and modification, improving the homogeneity of filling materials and laying the foundation for uniform compaction.

3.2 Layered Compaction Technology.

Layered compaction is critical for subgrade bearing capacity and stability. Based on the sludge's characteristics, key parameters (layer thickness, compaction machinery, process) were optimized through field trial compaction.

3.2.1 Filling Thickness Control.

Excessive layer thickness limits compaction energy transmission, while insufficient thickness reduces efficiency. Combining compaction test results and engineering experience, the layer thickness was controlled at 20-30cm. Field trial compaction confirmed 25cm as optimal—ensuring compaction energy penetrates to the layer bottom while balancing construction efficiency.

3.2.2 Compaction Machinery Selection.

Compaction machinery was selected based on sludge properties and layer thickness. Static rollers (suitable for fine-grained soil but poor effect), vibratory rollers (good compaction via vibration), and sheep foot rollers (effective for cohesive soil) were compared. Field tests showed that a 20t vibratory roller achieves the best effect: 6-8 passes result in compaction degree $\geq 93\%$. Sheep foot rollers were used for auxiliary compaction in poorly compacted areas. This selection targets the sludge's fine-grained, high-plastic characteristics, addressing the challenge of low compaction efficiency for such materials.

3.2.3 Compaction Process Determination.

The compaction process follows "light first, heavy later; slow first, fast later; edge first, middle later":

- (1) Static pressure for 2 passes to evenly distribute and initially compact the sludge;
- (2) Vibratory compaction for 4-6 passes at 2-3km/h;
- (3) Static pressure for 2 passes to smooth the surface.

This process ensures gradual particle densification, avoids surface compaction before internal densification, and improves overall compaction quality. Real-time monitoring of compaction status allows adjustment of rolling passes, adapting to on-site moisture content and sludge uniformity variations.

3.3 Quality Control Technology

The quality control of layered filling subgrade with shield drilling sludge runs through the whole construction process^[14-16], including the quality control of raw materials, the quality control of construction process and the quality detection of finished subgrade.

3.3.1 Quality Control of Raw Materials.

Before the sludge is used for filling, the physical and mechanical properties of the sludge should be tested, including moisture content, particle size distribution, compaction characteristics, shear strength and other indicators, to ensure that the sludge meets the requirements of subgrade filling after pretreatment. At the same time, the quality of modifiers (such as lime) should be checked to ensure that their performance meets the relevant standards.

3.3.2 Quality Control of Construction Process.

In the process of layered filling and compaction, the following aspects should be controlled: first, the filling thickness of each layer should be strictly controlled, and the thickness should be measured by a measuring instrument, and the deviation should not exceed $\pm 5\text{cm}$; second, the moisture content of the filling sludge should be checked at any time, and if it is too high or too low, it should be adjusted by adding water or drying; third, the compaction machinery and compaction process should be strictly implemented according to the determined scheme, and the number of rolling passes should be recorded; fourth, the surface of the filling layer should be kept flat and free of pits and bulges, and the slope should meet the design requirements.

3.3.3 Quality Detection of Finished Subgrade.

After each layer's compaction, key indicators are detected: (1) Compaction degree (ring knife/sand filling method, 3 points per 1000m^2 , $\geq 93\%$ for subgrade bottom layer/embankment); (2) Bearing capacity (dynamic cone penetration/plate load test, dynamic cone penetration resistance $\geq 180\text{kPa}$); (3) Settlement (settlement observation points, stable settlement within design range). This post-construction detection verifies engineering effect and provides feedback for process optimization.

4 Field Test Verification

In order to verify the feasibility and engineering effect of the key technologies of layered filling subgrade with shield drilling sludge, a field test section is set up in a highway reconstruction project. The length of the test section is 200m , the width of the subgrade is 12m , and the filling height is 3m . The shield drilling sludge used in the test section is the same as that in the laboratory test, and the pretreatment and layered compaction technologies studied in this paper are adopted for construction.

4.1 Test Section Construction

The construction process of the test section is as follows^[17-18]: first, the original ground is leveled and compacted, and the compaction degree is required to be not less than 90%; then, the shield drilling sludge is pretreated (natural drying + mechanical dehydration + lime modification + screening), and the moisture content is adjusted to 28%; then, the pretreated sludge is filled in layers, each layer is 25cm thick, and the 20t vibratory roller is used for compaction according to the determined compaction process; finally, after the completion of all layers of filling, the quality detection of the finished subgrade is carried out.

4.2 Test Results and Analysis

4.2.1 Compaction Degree Detection.

A total of 60 compaction degree detection points are set in the test section, and the detection results show that the compaction degree of all detection points is between 93.5% and 96.8%, with an average value of 95.2%, which meets the requirement of not less than 93%. It can be seen that the layered compaction technology adopted in this study can effectively ensure the compaction quality of the subgrade.

4.2.2 Bearing Capacity Detection.

10 bearing capacity detection points are set in the test section, and the dynamic cone penetration test is carried out. The test results show that the dynamic cone penetration resistance of all detection points is between 185MPa and 220MPa, with an average value of 203MPa, which meets the design requirement of not less than 180MPa. It indicates that the filled subgrade has good bearing capacity.

4.2.3 Settlement Observation.

5 settlement observation points are set in the test section, and the settlement observation is carried out for 6 months. The observation results show that the total settlement of the subgrade is between 8mm and 12mm, and the settlement tends to be stable after 4 months, with no obvious uneven settlement. It shows that the filled subgrade has good stability and durability.

In addition, the environmental impact of the test section is monitored. During the construction process, the dust concentration and noise level around the test section are within the limits specified by the national standards, and there is no pollution to the surrounding soil and water bodies. After the completion of the test section, the vegetation around the subgrade grows normally, which shows that the layered filling of subgrade with shield drilling sludge has no obvious negative impact on the environment.

5 Conclusion and Prospect

5.1 Conclusion

This paper studies the key technologies of layered filling subgrade with shield drilling sludge, and draws the following conclusions:

(1) The shield drilling sludge is a kind of fine-grained soil with high content of clay and silt, high natural moisture content and good plasticity. Its physical and mechanical properties can be effectively improved after dehydration, modification and screening pretreatment. When 6% lime is added as modifier, the optimal moisture content of the sludge is 27.8%, the maximum dry density is 1.68g/cm³, the cohesive force c is 35.2kPa, and the internal friction angle φ is 21.5°, which meets the requirements of subgrade filling.

(2) The key technologies of layered filling subgrade with shield drilling sludge include sludge pretreatment technology, layered compaction technology and quality control technology. The pretreatment technology of "natural drying + mechanical dehydration + lime modification + screening" can effectively improve the physical and mechanical properties of the sludge; the layered compaction technology with filling thickness of 25cm, 20t vibratory roller as main compaction machinery and compaction process of "static pressure - vibratory compaction - static pressure" can ensure the compaction quality of the subgrade; the whole process quality control technology can ensure the engineering quality of the filled subgrade.

(3) The field test results show that the compaction degree, bearing capacity and stability of the subgrade filled with shield drilling sludge after pretreatment and layered compaction all meet the design requirements, and there is no obvious environmental impact. It is feasible to use shield drilling sludge for layered filling of subgrade, which can realize the resource utilization of sludge and has significant economic and environmental benefits.

5.2 Prospect

Although this study has achieved certain results, there are still some problems to be further studied:

(1) The research in this paper is aimed at the shield drilling sludge from a specific tunnel project. The properties of sludge from different stratum conditions and construction processes are different. Therefore, it is necessary to carry out targeted research on the pretreatment and filling technologies of sludge from different sources.

(2) The long-term performance of the subgrade filled with shield drilling sludge needs to be further monitored, including the changes of bearing capacity, stability and durability under the action of long-term vehicle load and natural environment.

(3) The cost-benefit analysis of layered filling subgrade with shield drilling sludge needs to be further carried out, and the optimization scheme of technology and economy should be put forward to promote its wide application in engineering practice.

In the future, with the continuous improvement of shield drilling sludge pretreatment technology and layered filling technology, it is believed that shield drilling sludge will

be more widely used in subgrade engineering, which will make positive contributions to the sustainable development of engineering construction and environmental protection.

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