Technological and Managerial Innovation and Application Practice of Shield Residue Soil Premixed Mortar

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Abstract*—Against the backdrop of China's drive to achieve a comprehensive green transformation of economic and social development and its implementation of the "Dual Carbon" strategy, the large-scale resource utilization of residue soil generated by shield tunneling has become one of the core topics for green and low-carbon development in the construction sector. Traditional shield grouting materials rely on primary resources such as sand, gravel, and cement, resulting in high costs, significant carbon emissions, and serious ecological damage. Meanwhile, the disposal of shield residue soil is difficult due to strict off-site dumping regulations, high safety risks, and mounting environmental pressure—all of which have become bottlenecks constraining the high-quality development of shield construction. This paper innovatively proposes a technology for manufacturing premixed mortar from shield residue soil: using shield excavation waste soil as the core raw material, and through undisturbed soil solidification technology, precise mix proportioning, and standardized process control, it prepares high-performance synchronous grouting premixed mortar. The paper systematically elaborates on the industry background, core principles, technical pathways, performance indicators, and benefit advantages of this technology. Combined with engineering practice in projects such as Nanjing Metro Line 6 and the extension of Ningbo Metro Line 4, the paper verifies its significant value in cost reduction and efficiency improvement, ecological and environmental protection, and construction safety. Research demonstrates that this technology achieves in-situ resource utilization of residue soil. Compared with traditional synchronous grouting mortar: the 7-day early compressive strength is improved by more than 60%, impermeability is enhanced by one order of magnitude, and initial setting time is reduced by 50%. It can effectively reduce ground settlement and segment floating, lower overall construction costs, and is aligned with the philosophy of green and low-carbon development, thereby providing a replicable and scalable technical paradigm for the resource utilization of construction waste from shield tunneling projects.

***Index Terms*—shield residue soil; premixed mortar; resource utilization; synchronous grouting; green construction; technological innovation**

I. Introduction

(I) Research Background and Policy Orientation

The Opinions on Accelerating the Comprehensive Green Transformation of Economic and Social Development, jointly issued by the Central Committee of the Communist Party of China and the State Council, clearly states that promoting the greening and low-carbonization of economic and social development is an important hallmark of the Party's new governance philosophy and new practice in the new era, thereby charting the course for green transformation in the construction sector. In recent years, local governments at all levels have successively introduced special policies on the resource utilization of construction waste, designating the recycling of engineering waste as a key measure to implement the green development concept and advance ecological civilization—compelling the construction industry to abandon the traditional extensive development model and pursue a path of high-quality development characterized by resource conservation and environmental friendliness.

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As China's urban rail transit, utility tunnels, highway and railway tunnels, and other projects advance rapidly, shield tunneling has become the mainstream method for underground construction due to its high efficiency and minimal impact on the surrounding environment. According to statistics, shield tunnels currently under construction in China are projected to generate hundreds of millions of cubic meters of residue soil construction waste, accounting for 15%–20% of urban construction waste discharge, with residue soil transportation and disposal costs estimated to exceed tens of billions of yuan. In shield tunneling, tail-void synchronous grouting is the core procedure for controlling ground settlement and ensuring the waterproofing performance of tunnels. Traditional grout uses sand and gravel, fly ash, cement, and bentonite as its main raw materials, which not only incurs high procurement and transportation costs but also generates significant carbon emissions and ecological damage in the production and transportation stages. Excessive extraction of sand and gravel has led to increasingly scarce natural resources and continuously rising prices, substantially driving up shield construction costs. Meanwhile, traditional residue soil disposal mainly relies on off-site dumping; strict receiving capacity controls in many regions and closure of dumping sites during rainy weather directly impede shield boring progress; soil accumulation also triggers ecological and safety risks such as landslides and soil contamination, all of which are pressing pain points for the shield construction industry.

(II) Core Problems in the Industry

1. Dual escalation of raw material costs and environmental pressure. Traditional grouting materials rely on primary sand, gravel, and cement. The production and transportation stages generate high carbon emissions and cause significant ecological damage; raw material prices are subject to considerable market volatility and account for a large proportion of shield construction costs, continuously squeezing enterprise profit margins.
2. Prominent difficulties in residue soil disposal. Off-site dumping is subject to strict regional controls, disposal sites are scarce, transportation costs are high, and the process easily contaminates roadside environments; soil cannot be transported normally during rain and other adverse weather conditions, directly delaying construction schedules; accumulated soil poses safety hazards such as landslides and seepage pollution, which are inconsistent with ecological and environmental protection requirements.
3. Serious homogenization of the premixed mortar market. Traditional premixed mortar production is constrained by raw material and transportation costs; product performance is homogenized with little core competitiveness, and it is difficult to meet the demands of shield construction for high efficiency, high quality, and green development.

Against this background, developing new technologies for resource utilization of shield residue soil—transforming waste soil into high-performance grouting premixed mortar and achieving "turning waste into treasure, in-situ consumption, cost reduction and efficiency improvement"—is both an imperative response to national green low-carbon development policies and an innovative pathway to resolve industry pain points and promote green transformation in the construction sector. It carries significant theoretical value and practical engineering significance.

II. **C**ore Technical Principles of Shield Residue Soil Premixed Mortar

(I) Core Technical Concept

The shield residue soil premixed mortar technology takes undisturbed soil solidification technology as its core. It breaks the limitations of traditional grouting materials' reliance on primary resources by directly utilizing engineering waste such as shield excavation residue soil and foundation pit spoil as the main raw materials, thereby abandoning the mode of off-site dumping and achieving in-situ resource recycling at the construction site. Through precise proportioning of supplementary cementitious materials such as cement and soil hardeners, combined with professional mixing processes, it prepares premixed mortar that meets the specification requirements for shield synchronous grouting, balancing grout performance, construction efficiency, and environmental benefits to achieve the technical goals of "environmental friendliness, resource recycling, cost reduction and efficiency improvement."

(II) Raw Material Adaptation and Mix Design

1. Core raw material: The shield residue soil excavated in situ at the construction site serves as the main component, eliminating the need for additional transportation and procurement of sand and gravel, significantly reducing raw material procurement and transportation costs while achieving zero off-site transportation and zero disposal of a

portion of the residue soil. For the specific geological conditions of each project (such as miscellaneous fill, silty clay, soft silty soil, weathered rock, etc.), samples are collected on site in advance and multiple batches of mix-proportion trials are conducted in the laboratory to analyze the particle size distribution, moisture content, organic matter content, and other indicators of the residue soil, thereby determining the optimal raw material ratio.

2. Auxiliary materials: Ordinary Portland cement and specialized soil hardeners are selected as cementitious materials, supplemented by appropriate admixtures to regulate the fluidity, setting time, strength, and impermeability of the grout, ensuring that the grout meets the shield grouting requirements for different strata and different construction conditions.

3. Customized mix design: The proportioning of auxiliary materials is flexibly adjusted according to the project's construction schedule, geological conditions, and grouting requirements, enabling precise control of grout strength, setting time, and fluidity to meet the individualized construction demands of different projects. Standardized laboratory test reports are issued to ensure that grout performance complies with national and industry specifications.

III. **T**echnical Pathway and Process Control of Shield Residue Soil Premixed Mortar

(I) Overall Process Flow

Taking into account the geological conditions and construction characteristics of conventional shield projects, the shield residue soil premixed mortar process is divided into two core stages: preparation of residue soil slurry and preparation of finished grout. The entire process forms a closed-loop production cycle at the construction site, with a straightforward workflow and strong operability.

1. Preparation of residue soil slurry: The residue soil generated by shield excavation is collected and screened on site to remove impurities, then fed into dedicated mixing equipment. In accordance with the moisture content standard determined by laboratory tests, an appropriate amount of clean water is added and mixed to produce a uniform, lump-free undisturbed soil slurry, from which large-particle impurities are removed to ensure that the particle size distribution of the subsequent grout meets the required standards.

2. Preparation of finished grout: To the prepared undisturbed soil slurry, cement, soil hardeners, and admixtures are added in precise proportions. The mixture is thoroughly blended using a fully automatic mixing system with strict control of mixing time and speed to ensure homogeneous integration of all raw materials, producing shield synchronous grouting premixed mortar that meets the required performance indicators, which is then delivered directly to the shield grouting equipment for use.

(II) Site Layout Requirements

This technology has flexible site requirements and can adapt to various shield construction site conditions. The standard footprint is approximately 750 m^2 (30 m × 25 m) and can be flexibly adjusted to suit the available space and construction layout, requiring no large-scale site modifications. Within the site, designated zones are rationally delineated for residue soil collection, slurry preparation, premixed mortar mixing, raw material storage, and equipment operation, achieving zoned process flow and standardized operations to ensure production safety and construction efficiency.

(III) Key Points of Technological and Managerial Innovation

1. Pre-construction test control: Field sampling and laboratory testing of residue soil are conducted before construction, establishing a "one project, one mix" mechanism whereby a customized proportion is tailored to the specific geological conditions of each project, ensuring at the source that mortar performance meets the required standards.

2. Full-process quality control: During production, real-time monitoring is conducted for slurry moisture content, mixing uniformity, and grout fluidity. A quality traceability system is established to ensure stable performance in every batch of premixed mortar.

3. Standardized operation management: Dedicated construction process manuals and operating procedures are developed; professional training is provided to operators; and the processes of residue soil treatment, proportioning and measurement, mixing, and grouting are standardized, achieving standardized and regulated technical implementation.

IV. Comparative Analysis of Performance Indicators of Shield Residue Soil Premixed Mortar

To verify the performance advantages of shield residue soil premixed mortar, it is compared against traditional inert mortar and traditional hardenable mortar across four core indicators: compressive strength, bond strength, impermeability grade, and setting time. The results are shown in the table below:

Performance Indicator	Shield Residue Soil Premixed Mortar	Traditional Inert Mortar	Traditional Hardenable Mortar	Performance Advantages of Shield Residue Soil Premixed Mortar
Compressive Strength	7d ≥ 0.5 MPa; 28d ≥ 2.5 MPa	28d ≥ 0.3 MPa	7d ≥ 0.5 MPa; 1.0 MPa ≤ 28d ≤ 2.5 MPa	Rapidly forms load-bearing structure, reduces ground settlement risk
Bond Strength	≥ 2.5 MPa with segment concrete	≤ 0.3 MPa with segment concrete	≥ 1.0 MPa with segment concrete	Bond strength improved by over 50%; prevents debonding from segments and ensures waterproof sealing
Impermeability Grade	Permeability coefficient ≤ 1×10^{-8} cm/s	Permeability coefficient ~1×10^{-6} cm/s	Permeability coefficient ~1×10^{-7} cm/s	Impermeability improved by one order of magnitude; blocks groundwater seepage and reduces secondary grouting
Setting Time	Initial set: 4–8 h (adjustable)	Initial set: > 16 h	Initial set: > 12 h	Setting time reduced by 50%; rapid void filling; compatible with high-speed TBM tunneling

(I) Core Performance Advantages

1. Excellent strength performance: Meets the specification requirements of ≥ 0.8 MPa at 7 days and ≥ 2.5 MPa at 28 days for shield grouting; later-age strength can be flexibly adjusted; good durability; rapidly forms a load-bearing structure and effectively controls ground deformation.
2. Good construction performance: Excellent fluidity and self-compaction. Field tests show a slump of 26.0–28.7 cm at 0 h and 21.2–27.3 cm at 8 h; bleeding rate is stably controlled at 1%–2%, meeting pumpability requirements; void filling is dense with low shrinkage.
3. Controllable setting time: Initial and final setting times can be flexibly adjusted based on TBM boring speed and stratum conditions to suit different construction scenarios, avoiding construction delays caused by excessively fast or slow grout setting.
4. Outstanding environmental performance: Using waste residue soil as the main raw material reduces the consumption of primary sand, gravel, and cement, decreasing resource consumption and waste discharge, in alignment with the concept of green low-carbon and circular economy development.

V. Benefit Analysis of Shield Residue Soil Premixed Mortar

(I) Economic Benefits

1. Reduction of raw material costs: Using waste residue soil as the core raw material substantially reduces procurement and transportation costs for externally sourced raw materials such as sand, gravel, and cement; production costs are further lowered as production scales up.
2. Savings in residue soil disposal costs: In-situ resource utilization of residue soil is achieved, reducing the volume of off-site transportation and cutting residue soil disposal costs by approximately 7%, while eliminating additional expenses such as dump site land rental and environmental remediation.
3. Reduction of long-term maintenance costs: The excellent impermeability of the grout results in fewer leakage points and smaller deformation in the completed tunnel, significantly reducing costs for secondary grouting and long-term tunnel maintenance. Additionally, projects do not need to construct their own grout stations, eliminating construction, operation, and labor costs for such stations; the enterprise supplies premixed mortar directly, making construction more convenient.

(II) Environmental Benefits

1. Resource recycling: Transforming large volumes of shield residue soil from waste to value achieves in-situ

consumption of engineering waste, reducing the occupation of land resources and the pollution of the ecological environment by construction waste.

2. Significant carbon reduction and emission reduction effects: Carbon emissions from sand and gravel extraction, cement production, and long-distance transportation of raw materials are reduced; dust and noise pollution during construction are minimized; and green construction requirements are fulfilled.

3. Mitigation of ecological safety risks: Problems such as landslides and seepage contamination caused by residue soil accumulation are eliminated, in compliance with relevant policies on ecological and environmental protection and work safety.

(III) Construction Benefits

1. Ensuring construction schedule: Reducing off-site residue soil transportation avoids construction stoppages caused by dump site closures during rainy weather, ensuring continuous shield boring and improving construction efficiency.

2. Improving project quality: Grout performance surpasses that of traditional mortar, effectively controlling ground settlement, tunnel settlement, leakage, and segment floating, thereby improving the formation quality and durability of the completed tunnel.

VI. **E**ngineering Application Practice and Verification of Results

(I) Monitoring Data from Trial Section Application

A representative shield construction section was selected for trial application. Full-process monitoring was carried out on grout performance, ground settlement, tunnel deformation, and other indicators, with results as follows:

1. Grout performance: Third-party testing shows compressive strength of ≥ 0.5 MPa at 3 days, ≥ 1 MPa at 7 days, and ≥ 2.5 MPa at 28 days; bleeding rate ≤ 2%, stabilizing at 0.5%–1% at a later stage; slump change over time is small—fully meeting the requirements for shield grouting construction.

2. Surrounding ground settlement: When using traditional grout, the average ground settlement was 10.2 mm; after adopting residue soil premixed mortar, the average settlement was 8 mm, a reduction of 21.6%.

3. Tunnel settlement: Average tunnel settlement with traditional grout was 0.86 mm; with the new grout it was reduced to 0.43 mm, a reduction of 50%.

4. Segment floating: Traditional grout resulted in segment floating of 20–25 mm; the new grout controls it to 10–15 mm, a reduction of approximately 50%, effectively ensuring the dimensional accuracy of the formed tunnel segments.

5. Tunnel convergence: Tunnel convergence deformation under the new grout is slightly improved, further enhancing structural stability.

(II) Typical Engineering Cases

1. A certain section of Nanjing Metro Line 6: The technology was put into service at the end of 2022; the interval was completed in January 2024. More than 8,000 m³ of grouting material was cumulatively injected and shield boring exceeded 2,000 m. During construction, the TBM traversed complex strata including miscellaneous fill, silty clay, weathered rock, and cobblestone, successfully passing through multiple risk sources such as buildings and watercourses. The quality of the formed tunnel was excellent with no leakage or segment floating problems, and construction costs were reduced by more than 15% compared with the same period in previous years.

2. Extension section of Ningbo Metro Line 4: The technology was applied in July 2023 and the section was completed in early 2024. Grouting volume exceeded 6,000 m³ and boring exceeded 1,500 m. The TBM traversed weak and complex strata including soft mud, soft plastic clay, and tuffite, successfully passing through the core area of East Qian Lake. The technology completely resolved the segment floating problem caused by traditional grout; waterproofing performance met the required standards; construction schedule and project quality both met project requirements; and the technology was highly commended by the project owner.

VII. **C**onclusions and Outlook

(I) Research Conclusions

The shield residue soil premixed mortar technology closely aligns with the national strategy for green and low-carbon development. With resource utilization of engineering waste at its core, it combines technological and managerial innovation to resolve the industry pain points of high raw material costs, difficult residue soil disposal, and heavy environmental pressure in traditional shield construction. Using waste residue soil as the main raw material, the process is straightforward and highly adaptable to different sites. The prepared premixed mortar outperforms traditional mortar in terms of strength, impermeability, bond strength, and setting time, effectively improving tunnel construction quality and ensuring construction schedules. At the same time, it achieves significant economic, environmental, and construction benefits, is in line with the requirements for ecological civilization construction and the green transformation of the construction industry, and has strong potential for widespread application.

(II) Development Outlook

Looking ahead, the mix design system of the shield residue soil premixed mortar can be further optimized to adapt to more complex geological conditions and special construction scenarios. By integrating intelligent and digital technologies, full-process automated control of residue soil treatment, proportioning and measurement, and mixing and grouting can be achieved, elevating the level of technical standardization and intelligence. Efforts should also be made to promote the inclusion of this technology in the promotion catalog for resource utilization of construction waste, improve relevant industry standards and norms, and help the shield tunneling industry in China comprehensively achieve green, low-carbon, and high-quality development, contributing innovative engineering solutions to the acceleration of a comprehensive green transformation of economic and social development.

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