

Research Progress of Grouting Materials at Home and Abroad and Future Development Trends

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Abstract

Grouting technology is a core reinforcement and anti-seepage method in the field of geotechnical engineering, and its application efficiency relies critically on the performance breakthrough and technological innovation of grouting materials. In recent years, the research on grouting materials worldwide has entered a period of rapid development. Scholars at home and abroad have conducted in-depth exploration around the core directions such as material research and development, performance evaluation, and construction application, and have achieved a series of results with practical value and theoretical significance. At the same time, they are also facing common challenges such as deepening basic research and improving the technical system. This paper systematically elaborates on the research status at home and abroad, core differences and future development trends from three aspects.

Keywords

Grouting Materials, Geotechnical Engineering, Performance Evaluation, Construction Technology, Research Progress.

1. Introduction

Grouting technology is a core reinforcement and anti-seepage method in the field of geotechnical engineering, and its application efficiency relies critically on the performance breakthrough and technological innovation of grouting materials. In recent years, the research on grouting materials worldwide has entered a period of rapid development. Scholars at home and abroad have conducted in-depth exploration around the core directions such as material research and development, performance evaluation, and construction application, and have achieved a series of results with practical value and theoretical significance. At the same time, they are also facing common challenges such as deepening basic research and improving the technical system. The following systematically elaborates on the research status at home and abroad, core differences and future trends from three aspects.

2. Research Progress of Grouting Materials in China

The research on grouting materials in China relies on the demand for large-scale infrastructure construction (such as high-speed railway tunnels, water conservancy hubs, urban underground projects, etc.), forming a research pattern of "demand-oriented, industry-university-research collaboration". It has achieved remarkable results in material innovation, evaluation system construction and technology optimization, providing solid support for engineering practice.

2.1. Research and Development of New Grouting Materials: Focus on Functional and Environmental Transformation

In recent years, aiming at the complex geotechnical engineering conditions in China, breakthroughs have been made in the performance bottlenecks of traditional grouting

materials, and a number of new grouting material systems with high adaptability have emerged, becoming a core research hotspot.

(1) Nano-material grouting: By introducing nano-scale powders (such as nano-silica, nano-calcium carbonate, nano-clay, etc.) or preparing nano-composite systems, the permeability and curing strength of grouting materials are significantly improved. Nano-particles can penetrate into the micro-pores and cracks of geotechnical mass, fill the pore structure and form a dense reinforcement layer, solving the problems of insufficient penetration and limited reinforcement effect of traditional materials in low-permeability geotechnical mass. At the same time, the incorporation of nano-materials can optimize the curing time and volume shrinkage rate of the material, adapting to the construction needs of different engineering scenarios. Wang et al. used ultra-fine Portland cement as the cementitious material and prepared high-strength composite grouting materials by modifying with nano-SiO₂. The study found that the mechanical properties of the material were optimal when the dosage was 1%, and the 1-day compressive and flexural strengths of the stone body were increased by 49.6% and 91.4% respectively. The reinforcement mechanism mainly comes from the synergistic effect of the micro-aggregate filling effect, pozzolanic effect and nucleation effect of nano-SiO₂[1].

(2) Biological material grouting: Based on the principle of microbial mineralization (such as microbial-induced calcium carbonate precipitation, microbial-induced silicate precipitation, etc.), environmentally friendly biological grouting materials have been developed. This type of material uses microbial metabolites to chemically react with geotechnical components to generate calcium carbonate or silicate crystals, realizing the pore cementation and strength improvement of geotechnical mass. It has the advantages of no secondary pollution and adaptation to in-situ reinforcement, and has been pilot applied in ecological restoration geotechnical projects[2]. Wu et al. systematically summarized the research progress of foundation treatment based on MICP (microbial-induced calcium carbonate precipitation) technology, pointing out that this technology can effectively control the seepage of geotechnical mass and enhance the soil strength by reproducing the natural rock-forming process, and has prominent advantages such as environmental friendliness and good fluidity, showing broad application prospects in the field of geotechnical engineering[3].

(3) Composite modified grouting materials: Aiming at the performance shortcomings of single materials, research on composite modification of traditional materials such as cement-based, fly ash-based and slag-based materials has been carried out. By adding admixtures, fiber materials, etc., composite grouting materials with comprehensive properties such as high fluidity, early strength, impermeability and crack resistance have been prepared, which greatly expand the application boundary of traditional materials and reduce engineering costs[4]. Zhang et al. carried out experimental research on the engineering characteristics of red mud-based green high-performance grouting materials, confirming that this type of composite modified material can realize the resource utilization of industrial solid waste, taking into account environmental protection and engineering performance[5].

2.2. Performance Testing and Evaluation of Grouting Materials: Construction of Systematic and Standardized System

Scholars in China have carried out a large number of systematic experimental studies around the core needs of engineering applications of grouting materials, and gradually established a test and evaluation system covering all performance dimensions of materials, providing a scientific basis for material research and development and engineering selection[6].

(1) Improvement of core performance evaluation system: A multi-dimensional evaluation index library has been constructed for the key indicators of grouting materials, such as reinforcement effect, mechanical properties, permeability, environmental performance and durability. Through indoor triaxial tests, direct shear tests, permeability tests, freeze-thaw cycle

tests, etc., the correlation between material parameters and the improvement of geotechnical performance is quantitatively analyzed; for environmentally friendly grouting materials, special evaluation standards such as heavy metal leaching, biological safety and degradability have been established, filling the gap in the performance evaluation of environmentally friendly materials[7]. Chen et al. systematically studied the durability of ternary geopolymer grouting materials based on the response surface method, improving the durability evaluation method of composite grouting materials[8].

(2) Innovation of evaluation methods and promotion of standardization: Combined with numerical simulation technology and field tests, a numerical simulation evaluation method for the reinforcement effect of grouting materials based on software such as FLAC3D and MIDAS has been developed, realizing the joint verification of indoor experiments and field applications; at the same time, active promotion of the formulation of industry standards and national standards has been carried out, taking the lead in completing the compilation of a number of grouting material performance test specifications, unifying test procedures, index thresholds and evaluation methods, and improving the standardization and promotion of research results[9]. Zhong et al. constructed a mathematical model for evaluating grouting effect based on fuzzy mathematics principle, combining grouting volume calculation method, inspection hole analysis method and other detection methods for water-rich sand tunnel grouting reinforcement project, which was applied to the sand tunnel project of Zhengzhou Metro Line 7, verifying the scientificity and efficiency of the evaluation method and providing a reference for similar projects[10].

2.3. Optimization of Grouting Material Construction Technology: Realizing Efficient and Intelligent Upgrade

To adapt to the performance characteristics of new grouting materials, scholars in China have focused on the optimization of construction technology, equipment and processes, promoting the development of grouting construction technology towards high efficiency, precision and intelligence[11].

(1) Innovation of grouting technology: A variety of construction technologies such as segmented grouting, sleeve valve pipe grouting, high-pressure jet grouting and double-liquid grouting have been developed for different types of geotechnical mass and material characteristics. By optimizing parameters such as grouting pressure, grouting volume and grouting sequence, combined with real-time monitoring of geotechnical geological conditions, the precise penetration and uniform distribution of grouting materials are realized, solving the problems of material waste, uneven reinforcement and low construction efficiency in traditional construction[12].

(2) Intelligent upgrading of construction equipment: New supporting grouting equipment has been developed, such as intelligent grouting pumps, automatic grouting recorders and ground-penetrating radar detection equipment, realizing real-time monitoring, data collection and dynamic regulation of parameters such as pressure, flow rate and grouting volume during the grouting process. At the same time, combined with the Internet of Things technology, an intelligent monitoring system for grouting construction has been built, realizing the remote transmission and analysis of construction data, and improving the controllability of the construction process and the reliability of the grouting effect[13]. Song et al. developed intelligent grouting equipment and applied it to the plain fill grouting reinforcement test. The study found that the equipment can quickly determine the appropriate grouting parameters, record construction data in real time, effectively improve grouting accuracy and construction efficiency, and provide technical support for plain fill foundation grouting reinforcement[14].

3. Standardization of construction processes: For typical engineering scenarios (such as tunnel grouting, foundation pit anti-seepage grouting, subgrade reinforcement grouting, etc.),

standardized construction processes and quality control systems have been formulated, clarifying the requirements of all links such as construction preparation, on-site operation, effect detection and emergency treatment, greatly reducing construction risks and ensuring the construction quality and safety of grouting projects[15]. Qu et al. applied the impact echo method to the detection of grouting compactness of prestressed pipelines, improving the detection process of grouting construction effect and providing technical support for construction quality control[16].

3. Research Progress of Grouting Materials Abroad

The research on grouting materials abroad started earlier. Relying on the mature geotechnical engineering theory system and high-end equipment technology, it is in a leading position in material innovation, construction technology innovation and engineering application expansion, forming a research model of "basic research leading, engineering application driving"[17].

3.1. Research and Development of New Grouting Materials: Leading the Direction of High-end and Customization

In the research and development of new grouting materials, foreign scholars focus on the direction of high-end functionalization and customization, and have developed a series of material systems with international leading level, providing core support for the global development of grouting technology[18].

(1) Microbial material grouting: It is at the international forefront in the field of microbial-induced mineralization grouting technology, conducting in-depth research on basic issues such as microbial strain screening, culture condition optimization and mineralization reaction mechanism, and developing customized microbial grouting systems suitable for different types of geotechnical mass. At the same time, the performance of microorganisms is improved through genetic engineering technology, which enhances the environmental adaptability and curing efficiency of grouting materials, and promotes the technology from laboratory research to large-scale engineering application[19].

(2) Polymer grouting materials: A series of high-performance polymer grouting materials have been developed, such as polyurethane, epoxy resin and acrylamide. This type of material has the advantages of high elasticity, high adhesion, rapid curing and chemical corrosion resistance, adapting to geotechnical reinforcement, leakage plugging and other scenarios under complex geological conditions, especially widely used in tunnel waterproofing, underground engineering anti-seepage and other projects. In addition, in response to environmental protection needs, degradable polymer grouting materials have been developed to gradually replace traditional high-pollution materials[17]. Studies have shown that polyurethane grouting materials have become one of the most widely used and rapidly developing grouting materials due to their appropriate viscosity, controllable curing time and excellent bonding performance. Through modification technologies such as temperature reduction, flame retardancy and mechanical enhancement, their application scope can be further expanded; as a lightweight organic polymer grouting material, polyurethane slurry also has excellent water impact resistance, high expansion rate and durability, and performs well in mine crack filling and water plugging reinforcement[18].

(3) Ultra-high performance grouting materials: Focusing on extreme engineering conditions (such as deep underground projects, high-stress geotechnical projects), ultra-high performance grouting materials with ultra-early strength, ultra-high strength and high toughness have been developed. Through molecular design and material composite technology, the microstructure of the material is regulated, realizing the synergistic improvement of material strength,

toughness and durability, and meeting the engineering reinforcement needs under extreme working conditions[20]. In addition, alkali-activated polymers, as low-carbon cementitious materials based on industrial solid waste, have broad application prospects in the reinforcement and water plugging of grouting projects.

3.2. Innovation of Grouting Material Construction Technology: Moving towards a New Stage of Intelligence and Automation

Relying on high-end equipment manufacturing and intelligent control technology, foreign countries have promoted the transformation of grouting construction technology from mechanization to intelligence and automation, greatly improving construction efficiency and the accuracy of grouting effect.

(1) Application of robot grouting technology: The in-depth integration of industrial robots, mobile robots and grouting technology has been realized, and grouting robots suitable for different engineering scenarios have been developed. For example, tunnel grouting robots can realize integrated operations of precise positioning, automatic drilling and automatic grouting, adapting to the narrow and complex construction environment inside the tunnel; geotechnical reinforcement robots can automatically adjust grouting parameters and construction paths according to geological detection data, realizing the precise delivery of grouting materials. Robot grouting technology not only reduces labor intensity, but also improves the safety and controllability of the construction process.

(2) Comprehensive application of non-destructive testing technology: Non-destructive testing technologies such as ground-penetrating radar, ultrasonic testing and infrared thermal imaging have been used throughout the grouting construction process. Before construction, non-destructive testing technology is used to accurately detect the internal cracks, pore distribution and geological defects of geotechnical mass, providing a precise basis for the design of grouting schemes; during construction, the penetration range and curing process of grouting materials are monitored in real time, and construction parameters are adjusted in a timely manner; after construction, non-destructive testing technology is used to quantitatively evaluate the grouting reinforcement effect, realizing the full-process quality control of grouting projects.

(3) Research and development of green and low-carbon construction technology: Focusing on the "dual carbon" goal, green and low-carbon grouting construction technologies have been developed. For example, using renewable energy to drive grouting equipment, optimizing construction processes to reduce material loss and energy consumption, and promoting the transformation of grouting construction technology towards green and low-carbon. The research and development and application of alkali-activated polymer grouting materials are important manifestations of the development of foreign green grouting technology, which can realize the resource utilization of industrial solid waste and meet the needs of low-carbon development.

3.3. Application Research of Grouting Materials: Expanding Scenario-based and Large-scale Application

Foreign scholars pay attention to the in-depth integration of grouting materials and engineering scenarios, carry out multi-field and large-scale application research, and form rich engineering application cases and technical systems, providing practical support for the industrialization and promotion of grouting materials.

(1) Transportation engineering field: New grouting materials and construction technologies are widely used in transportation infrastructure projects such as subway tunnels, high-speed railway tunnels and highway tunnels. Aiming at the problems of tunnel collapse risk, broken surrounding rock and leakage, polymer material grouting, microbial grouting and other

technologies are used for surrounding rock reinforcement and anti-seepage plugging, ensuring the construction safety and operation stability of transportation projects.

(2) Water conservancy engineering field: In water conservancy projects such as dam anti-seepage, dyke reinforcement and reservoir danger removal and reinforcement, relying on high-performance grouting materials and precise construction technology, the anti-seepage and reinforcement of dam foundation and dam body are realized. High-pressure jet grouting, deep mixing grouting and other processes are used to build continuous anti-seepage curtains, solving the leakage problem of water conservancy projects and ensuring the flood control safety and operation efficiency of water conservancy projects.

(3) Construction engineering field: Environmentally friendly and efficient grouting materials are promoted in construction projects such as high-rise building foundation reinforcement, underground space development and existing building foundation treatment. The bearing capacity of existing building foundations is optimized through grouting technology to solve the problem of foundation settlement; in underground space development, grouting technology is used to reinforce surrounding rock to ensure the construction safety and structural stability of underground projects.

(4) Mine engineering field: Large-scale application research of grouting materials and technologies has been carried out in mine underground surrounding rock reinforcement, goaf treatment, mine leakage prevention and control, etc. Aiming at the complex geological conditions and high-risk working conditions of mines, ultra-high performance grouting materials and intelligent construction technologies are used to realize efficient reinforcement of mine surrounding rock and reduce the safety risks in the mine mining process. Due to their excellent performance, polymer grouting materials have been widely used in underground mine crack filling. Relevant studies have explored their diffusion characteristics through numerical simulation and experimental methods, providing theoretical support for engineering applications.

4. Comparison and Core Differences between Domestic and Foreign Research

4.1. Differences in Research Focus

Domestic research is mainly driven by engineering needs, focusing on the localization adaptation of new materials, the construction of standardized performance evaluation systems and the localization optimization of construction technologies. It closely carries out research around the practical problems in domestic large-scale infrastructure construction, with high achievement transformation efficiency and strong pertinence to engineering applications.

Foreign research is mainly led by basic theories, focusing on the micro-mechanism of new materials, the research and development of high-end functional materials and the underlying innovation of intelligent construction technologies. It has leading advantages in material molecular design, microbial mineralization foundation, core technologies of intelligent equipment, etc., and the research results have global promotion value.

4.2. Differences in Technological Development Paths

The technology of grouting materials in China presents a parallel development path of "traditional material modification + new material exploration + construction technology upgrading". It not only focuses on the optimization and improvement of traditional materials such as cement-based and fly ash-based materials to reduce engineering costs, but also actively layouts the research and development of new materials such as nano and biological materials to realize technological iteration; foreign countries present a development path of "high-end material research and development + intelligent technology integration + scenario-based

application deepening", focusing on the integration and innovation of high-end materials and intelligent equipment, and promoting the upgrading of grouting technology towards high-end and intelligent directions.

4.3. Differences in Application Scenario Layout

Domestic application scenarios are mainly large-scale infrastructure projects, such as high-speed railways, water conservancy hubs and urban underground comprehensive pipe corridors, and the research results are highly consistent with the needs of engineering construction; foreign countries have achieved multi-field full coverage. In addition to traditional fields such as transportation, water conservancy and construction, the application research in emerging scenarios such as deep-sea engineering, polar engineering and ecological restoration is more in-depth, with a more forward-looking layout.

5. Conclusion

At present, remarkable advances have been achieved in the research on grouting materials both domestically and internationally. China has cultivated prominent advantages in the localization of grouting materials, the customization of construction technologies and large-scale engineering applications, which provides solid technical support for the practice of domestic geotechnical engineering. By contrast, overseas research leads the global frontier in the development of novel grouting materials, the innovation of intelligent construction technologies and fundamental theoretical research, driving the evolution of grouting technology towards high-end and intelligent directions worldwide. Nevertheless, both domestic and international research are confronted with common challenges, including the insufficient depth of fundamental research, poor adaptability of grouting materials to extreme working conditions, slow industrialization process of eco-friendly grouting materials, and low level of full-process intellectualization in construction technologies.

For the future development of grouting material research, several key directions should be focused on. First, fundamental research needs to be further deepened: core issues such as the microstructure-performance correlation of grouting materials, the regulatory mechanism of microbial mineralization and the degradation law of polymer materials should be thoroughly investigated, the interaction mechanism between geotechnical mass and grouting materials should be clarified, and the correlation model between material parameters and the performance improvement of geotechnical mass should be optimized, so as to lay a solid theoretical foundation for material innovation. Second, the innovation and upgrading of grouting materials should be promoted: priority should be given to the R&D of eco-friendly, functional and ultra-high performance grouting materials with full degradability and adaptability to extreme working conditions such as deep underground and deep sea environments; the green and high-performance modification of traditional grouting materials should be advanced to balance material performance and application cost, with the in-depth R&D of low-carbon grouting materials such as alkali-activated polymers as a key direction for green material innovation. Third, the intellectualization of construction technologies should be realized: robot-based grouting, non-destructive testing and intelligent monitoring technologies should be integrated to construct a full-process intelligent management and control system for grouting construction; special grouting equipment and construction processes adapted to complex scenarios such as polar regions, deserts and deep underground areas should be developed to improve the environmental adaptability and construction efficiency of grouting technologies. Fourth, industry-university-research collaboration and industrialization should be strengthened: cooperative ties among universities, research institutes and enterprises should be enhanced to accelerate the transformation of laboratory research achievements into engineering applications; the performance evaluation standard system for grouting materials

should be improved to standardize the entire process of material R&D, production and application; the industrialized production of eco-friendly and intelligent grouting materials should be promoted to reduce application costs and expand the scope of popularization. Fifth, cross-field integration and innovation should be boosted: the in-depth integration of grouting material technology with artificial intelligence, big data, new materials and biotechnology should be driven to spawn new research directions and technical achievements, so as to meet the diversified and high-end development needs of the geotechnical engineering field.

In general, grouting material research is a core component of geotechnical engineering, and its development is closely linked to the demands of engineering construction and technological progress. With the increasing emphasis on fundamental research at home and abroad, the continuous advancement of technological innovation and the in-depth development of cross-field integration, grouting materials and their construction technologies are expected to achieve breakthroughs at a higher level, which will provide more robust technical support for the safe, green and efficient development of global geotechnical engineering.

Conflicts of Interest

The authors declare that they have no conflict of interest.

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