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Advancements and Applications of Polyurethane Curing Technology in Railway Track Bed Construction in China

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Abstract: This paper examines the application of polyurethane curing technology in the construction of railway track beds, with a specific focus on its implementation in China's rapidly developing railway infrastructure. The study begins by identifying the limitations of traditional ballasted track beds, especially under the demands of high-speed and heavy-load railways. It then methodically analyzes the advantages of polyurethane-cured track beds, highlighting their improved mechanical properties, including enhanced stability and durability. The paper further explores the benefits of transitioning to prefabricated polyurethane track beds, emphasizing significant cost reductions, better construction quality, and enhanced maintainability. Through a detailed review of experimental data and practical applications, the paper demonstrates the efficacy of polyurethane track beds in various railway settings. A critical part of the research involves optimizing the structural parameters of polyurethane track beds to achieve the best balance of mechanical and damping properties. The conclusion of the paper underscores the potential of polyurethane curing technology as a transformative approach to railway track bed construction, offering a solution to the challenges posed by traditional methods and aligning with the evolving needs of modern railways.

Keywords: Polyurethane curing; Railway track bed; Infrastructure optimization; Prefabricated construction

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1. Working principle and basic components of polyurethane-cured track beds

The curing of ballasted railway track beds involves the infusion or spraying of a curing material onto the gravel track bed once it meets the relevant design and construction standards, thus consolidating the granular track bed into a unified structure. The curing of ballasted track beds mainly involves two stages: rigid curing and elastic curing. Rigid curing, which utilizes cement mortar materials, has been progressively replaced by ballastless tracks; elastic curing primarily employs materials like asphalt, epoxy resin, and polyurethane. However, asphalt-cured track beds alter the fundamental function of ballasted beds, offering poor maintainability and a shorter service life. Due to the lack of toughness, poor impact resistance of epoxy resin, and the propensity for brittle failure, its practical application is limited. As one of today's six major synthetic materials, polyurethane, with its exceptional physical and mechanical properties, good environmental adaptability, and durability, has found widespread application in various fields and has become the main material and direction for the development of curing ballasted track beds.

Initially, railway tracks mainly utilized traditional ballasted beds, a design that, while simple, required frequent maintenance. With the growing demands of railway transportation and the development of high-speed railways, the limitations of traditional track bed structures began to become apparent, especially under high-speed and heavy-load conditions. To enhance the stability of railway lines and reduce maintenance demands, researchers began to explore new track bed materials and technologies. Polyurethane, a polymer material known for its unique elasticity and durability, was considered for use in railway track beds. Initially tested in experiments and small-scale projects, polyurethane-cured track beds showed that this material could significantly improve the stability and lifespan of track beds. As the technology matured and more successful cases emerged, polyurethane-cured track beds began to be applied more broadly in railway networks. These track beds have been laid in experimental sections totaling 5200 meters on lines such as the Beijing-Guangzhou, Shanghai-Chengdu, Longzhang, Wari, and Daxi Passenger Dedicated Lines, covering conditions such as mixed passenger and freight transport, heavy loads, and high speeds of 250 and 350 km/h.

The polyurethane materials currently used for ballast bonding and curing mainly consist of polyisocyanates (Component A) and polymer polyols (Component B), forming a spatial network structure through covalent bonds. Component A typically comprises one or several mono-, di-, or polyisocyanate monomers, polymers, and prepolymers; Component B is made up of one or several polyether (or ester) polyols, catalysts, blowing agents, chain extenders, antioxidants, fillers, etc [1].

During the construction of a track bed, polyurethane is injected in the form of liquid into the gravel track bed. It then undergoes a chemical reaction to cure, forming an elastic solid. This process involves polymerization and crosslinking reactions, ultimately producing a continuous, elastic, and integral structure. The cured polyurethane structure exhibits excellent elasticity and compressive properties, effectively binding the gravel particles together and enhancing the overall stability and load-bearing capacity of the track bed. In the cured track bed, polyurethane serves as an effective damping layer, helping to reduce vibration and noise, a feature particularly important for railways located in urban or densely populated areas.

2. The advantages of polyurethane track beds

Firstly, a polyurethane-cured track bed is not a granular structure but a consolidated, integral one. Under the impact and vibrational load of trains, there is no relative displacement between ballast particles, thus reducing residual deformation of the track bed. Moreover, the gaps between gravel particles are filled with compressed expanded polyurethane, partially transferring forces and reducing stress at the contact points (surfaces) of the gravel particles. This delays the breakage and pulverization of ballast particles, consequently decreasing the cumulative deformation of the track bed.

Secondly, the polyurethane interspersed between the ballast particles in the cured track bed possesses elasticity, rendering the connections between these particles flexible. Hence, the internal structure of the polyurethane-cured track bed can tear along the polyurethane extrusion layer without causing damage to the ballast particles, ensuring good elasticity under train loads.

Thirdly, the cooperative working state between the polyurethane track bed and sleepers is similar to that of a gravel track bed. The relationship between the sleeper and the track bed is not completely consolidated. Utilizing the elasticity of the track bed not only prevents tamping between the bottom of the rail and the top surface of the track bed but also allows for the insertion or pouring of a layer between the bottom of the sleeper and the top surface of the track bed to elevate the rail, similar to ballast tamping or blowing operations on conventional tracks. This provides convenient maintenance conditions, meeting the repairability requirements of the track bed.

Fourthly, various aging tests demonstrate that the polyurethane foam material used in the polyurethane-cured track bed exhibits excellent aging resistance under harsh conditions.

Fifthly, polyurethane foam material possesses exceptional weather resistance, maintaining stable comprehensive performance over long periods under various external environments. Based on data from accelerated artificial wet-heat aging tests and using the time-temperature superposition method, the service life of polyurethane foam material used in polyurethane-cured track beds is estimated to be as high as 45.2 years [2]. The physical and mechanical properties of the polyurethane foam meet the load-bearing requirements of track beds in railway structures. The results of aging and weather resistance tests indicate that the polyurethane-cured track bed can adapt to different transportation environments, offering stable and reliable performance. The polyurethane foam material ensures the objective of maintenance-free service for up to 30 years. This is particularly significant for railway sections where maintenance and construction are impractical or inconvenient.

Sixthly, polyurethane curing materials bond well with the ballast, significantly increasing the longitudinal and lateral resistance of the track bed, and maintaining good track gauge stability. All dynamic test indicators are within the limits of the evaluation standards. Compared to ballastless tracks, polyurethane track beds reduce vibrations by 2.8 to 7.4 dB in the time domain and lower noise by 0.9 to 2.6 dB [3]. The comprehensive tests on the Daxi High-Speed Railway have successfully verified the excellent performance of the polyurethane-cured track bed, playing a significant role in enhancing the technology of ballasted tracks for China's high-speed railways and enriching the variety of high-speed railway track structures.

3. The prospects of polyurethane track bed curing technology in China

The direction of modern railway development is towards high-speed passenger and heavy-load freight services. By the end of 2014, China's high-speed railway operation mileage had surpassed 16,000 km, ranking first in the world. Of this, nearly 11,000 km are equipped with track beds, mainly used on all lines of 250 km/h high-speed railways except for tunnels over 6 km, and on large bridges and major stations of 300 km/h or faster railways. China is also a world leader in heavy-load railway technology. For instance, the Daqin Railway reached an annual transportation volume of 440 million tons in 2011, the highest globally. The 1269 km long Central-South Shanxi Railway Corridor started operations at the end of 2014, and the 1817 km long Mengxi to Central China coal transport corridor began construction at the end of 2012. These lines are characterized by their length, numerous tunnels (accounting for over 25%), and large axle loads (with a design axle load of 30 tons). Due to the prevalence of ballasted tracks in heavy-load railways, increased total weight leads to significant ballast breakage and pulverization, exacerbating track bed contamination. This causes a decrease or loss of track bed elasticity, deteriorating drainage capability, leading to damage to track components, exceeding geometric dimensions, and mud pumping and fouling issues, thereby significantly increasing maintenance. Particularly in tunnels, where maintenance environments are poor, and considering that some older heavy-load railway tunnels are not suitable for large screening machines, maintaining good track bed conditions is extremely challenging and has severely impacted the efficiency and safety of heavy-load transportation.

The most effective technical approach to improve the stability of visible tracks on large-span bridges of high-speed railways, switch areas, rail expansion joint areas, and the dirt and elasticity issues of ballasted tracks in heavy-load railways, is track bed solidification.

Therefore, polyurethane track bed curing technology has great development prospects in China.

(1) Research on combining ballast bonding with expanded solidification in the cured track bed structure

Fully leveraging the drainage performance of the ballast-bonded track bed eliminates the need for specific drainage design; capitalizing on the ability of the cured track bed to enhance elasticity.

(2) Developing a fastening system that complements polyurethane-cured track beds

When ballast bonding technology is applied to the transition section of ballastless and ballasted tracks, due to the superior elasticity of ballastless track fastenings, a sudden change in stiffness is likely at the junction of ballastless and ballasted tracks. Therefore, a fastening system for the ballasted track's ballast bonding area should be developed to ensure an even distribution of stiffness in the transition section.

(3) Developing low-expansion and environment-resilient polyurethane curing materials

By reducing the expansion force of polyurethane materials, the impact on track smoothness during construction is minimized, eliminating the need for pressure maintenance measures. Versatile polyurethane materials should be developed to reduce the cleanliness requirements of ballast and obviate the need for drying measures.

(4) Developing separate and portable unit-type construction equipment for drying and pouring processes

Current polyurethane-cured track bed construction equipment requires loading on 7 flat cars, which leads to low efficiency and multiple constraints on operational lines. Separating the drying and pouring processes and developing unit-type construction equipment can achieve high-efficiency operations within limited work windows.

(5) Developing simple, feasible, and economical maintenance and repair technologies

Due to the integrality of ballast bonding and cured track beds and the lack of maintenance experience, there is a need to study corresponding maintenance and repair methods for both dynamic and static changes and emergencies.

4. Limitations of polyurethane track beds

Firstly, the curing process of polyurethane places a high demand for the cleanliness and moisture content of the ballast. As a result, on-site cast polyurethane-cured track beds impose stringent requirements on every stage of ballast handling, including loading, unloading, storage, transportation, and compaction. Additionally, specialized equipment is needed to dry the ballast before pouring, leading to a substantial increase in construction costs. This contributes to the overall higher cost of constructing polyurethane-cured track beds.

Secondly, the requirements for ballast and structural cross-sections in polyurethane curing are based on existing design standards of high-speed railway ballasted tracks. However, the foaming of the polyurethane curing agent significantly enhances the mechanical properties of the original granular track bed. Continuing to use the existing design standards for high-speed ballasted track structures will inevitably lead to a conservative structural design with excessive safety redundancy, which is a major factor contributing to the high cost of polyurethane-cured track beds.

Thirdly, polyurethane-cured track beds constructed using on-site pouring methods exhibit good maintainability when dealing with issues like foundation settlement. However, they still present relatively challenging maintenance issues in situations like foundation heaving.

5. Advantages and suggested parameters of prefabricated polyurethane-cured track beds

Factory-based prefabrication of polyurethane-cured track beds, followed by modular construction on-site, can lead to a reduction in overall costs (more than 30% lower compared to cast-in-situ polyurethane-cured track beds), improvement in construction quality, and enhanced maintainability of the structure (enabling unit modular repairs).

Experimental studies have determined that prefabricated polyurethane cured track beds meet the requirements of the “High-Speed Railway Design Specifications,” indicating that the prefabricated polyurethane cured track bed structures possess adequate stability [4]. Prefabricated modular polyurethane cured track beds do not require routine maintenance and repair, offer good elasticity, and the section test results demonstrate that the stability and safety of operations are up to standard. This structure has a broad application prospect, particularly in sections with poor substructures or where routine maintenance is challenging.

As a novel track structure, the dimensions and density of prefabricated polyurethane-cured track beds can be precisely controlled during the preparation stage, helping to reduce production costs and extend the service life of the track bed. The thickness of polyurethane-cured track bed specimens is positively correlated with the amplitude of dynamic displacement. Although thinner cured track beds exhibit less residual deformation under load, their elasticity is lower, which is disadvantageous in attenuating intense upper train loads. Therefore, for lines with freight operations, the thickness of polyurethane-cured track beds should not be too small. The supporting stiffness of the track bed is negatively correlated with the thickness of the polyurethane-cured track bed beneath the sleeper. If the polyurethane track bed is too thick, it can lead to low stiffness and significant deformation during operation. Considering all factors, the thickness of prefabricated polyurethane-cured track beds for mixed passenger and freight railways should be between 28 and 32 cm. For easier fabrication, the recommended design thickness for mixed passenger and freight railway prefabricated polyurethane-cured track beds is set at 30 cm [5].

As the density, tensile strength, tear strength, and compressive strength of the polyurethane curing increase, the elongation at break first increases and then decreases, reaching a maximum at a density of 137 kg/m^3. The damping performance of polyurethane curing materials is linearly and positively correlated with the damping performance of their consolidated form. The damping performance of polyurethane curing materials is negatively correlated to the number of open-cell bubbles within the material. As the density of polyurethane curing material decreases, the number of open-cell bubbles in the material increases, enhancing energy absorption and improving damping effects. Considering both mechanical and damping properties, the ideal density of polyurethane curing materials should be between 140 and 170 kg/m^3 [6].

Disclosure statement

The author declares no conflict of interest.

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