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Analysis of mechanical properties of polyurethane-mixed ballast based on energy method

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HIGHLIGHTS

- The evolution law of macro energy was analyzed through the field test.
- The discrete element model of polyurethane-mixed ballast was established.
- The mechanical properties were analyzed using the energy method.

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ABSTRACT

The vertical loading-unloading trial was conducted on the polyurethane-mixed ballast of high-speed railway, obtaining the evolution law of macro energy of the polyurethane-mixed ballast. The discrete element model of the polyurethane-mixed ballast was established by PFC3D, and the parameters were calibrated and verified by the field test data. The evolution laws of micro energy of under the quasi-static load and trainload were analyzed. The results show that there were four main energies in the polyurethane-mixed ballast, namely elastic strain energy, viscous strain energy, friction energy and dashpot energy. The friction energy was the main form of energy, followed by the elastic strain energy. The viscous strain energy was larger than the dashpot energy under the quasi-static load, while the dashpot energy was larger than the viscous strain energy under the trainload. Under the quasi-static load, the elastic strain energy of the contact points between sleeper and ballast decreased at power rate, while other energy decreased exponentially. Under the trainload, the four kinds of energy of sleeper-ballast contact points decreased exponentially. The friction energy and elastic strain energy had a higher proportion on the bottom of sleeper. The viscous strain energy and dashpot energy had a higher proportion on the side of sleeper.

1. Introduction

The polyurethane-mixed ballast is a new type of track structure formed by spraying the polyurethane into the ballast, which has the characteristics of good stability and high rigidity [1]. The adhesive used in the construction of the polyurethane-mixed ballast usually contains two components, wherein the component A is isocyanate, and the component B is a mixture of polyether polyols, polyester polyols, chain extenders and the like. The two components are uniformly mixed and subject to a chemical reaction in a short time to generate the polyurethane cements [2,3]. In general, the polyurethane-mixed ballast is a track structure that is easy to construct and has good performance.

The polyurethane-mixed ballast is mainly used in the curve, turnout, transition and other weak links of railway to maintain the track stability and provide enough rigidity [4–6]. At present, the study on the mechanical properties of the polyurethane-mixed ballast is mainly based on the indoor model test. Woodward et al. [7] and Kennedy et al. [8] carried out a cyclic loading test on the polyurethane-mixed ballast through the indoor full-scale model, the results showed that the rigidity is improved and the cumulative settlement decreases obviously. Dersch et al. [9] and Boler et al. [10] found that the polyurethane-mixed ballast can effectively improve the shear strength and reduce the crushing of ballast through the indoor direct shear test, so that the stability of the polyurethane-mixed ballast is enhanced. In the numerical simulation, Woodward et al. [11,12] calculated the stress distribution and the resistance of the polyurethane-mixed ballast by establishing a finite element model.

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The above studies made a beneficial exploration on the macro mechanical properties of the polyurethane-mixed ballast. The indoor test and finite element analysis are the main methods at present. The indoor test often has the problems such as insufficient compactness and poor stability of the ballast so that it cannot accurately simulate the real state of ballast. The finite element method cannot reflect the micro contact characteristics of the polyurethane-mixed ballast.

Considering that the polyurethane-mixed ballast is a kind of non-ideal granular media, the micro-interaction between contact points is the intrinsic essence of its macro-mechanical properties, which fundamentally determines the stress and deformation modes of the ballast. For the polyurethane-mixed ballast in service, its mechanism under the trainload is essentially the process of energy storage, transformation and dissipation. Based on the first law of thermodynamics, the energy evolution law of the polyurethane-mixed ballast under the external load can be described macroscopically. Furthermore, the internal mechanism of energy evolution of the polyurethane-mixed ballast under the external load can also be revealed through micro-view. Therefore, the coupling analysis of macro and micro energy of polyurethane-mixed ballast can be realized and reveal the service performance more fundamentally, which also provides a new method for studying other mechanical properties of polyurethane-mixed ballast. The discrete element method (DEM) is an effective method to study the mechanical properties of granular materials, which can achieve accurate statistics of micro energy in different forms [13–15]. For the reason, this study first carried out the field trial in the polyurethane-mixed ballast at the high-speed railway, and analyzed the energy evolution of polyurethane-mixed ballast section from macro-perspective. Secondly, the commercial software PFC3D was used to establish the DEM of the polyurethane-mixed ballast, and the energy evolution under the quasi-static load and trainload was further analyzed from the micro-view, which provided a theoretical support for exploring the mechanical properties of polyurethane-mixed ballast.

2. The field trial and macro energy evolution

2.1. The vertical loading-unloading test

The polyurethane-mixed ballast was bonded in full cross-section at the test site, and the dosage of polyurethane was 48 kg/m^3. The field trial conducted the vertical loading-unloading test based on the support rigidity test of the ballast, as shown in Fig. 1. At the same time, the comparative trial was conducted in the common ballast section, as shown in Fig. 2.

In order to reflect the stress and deformation characteristics of the ballast reasonably, combined with the requirements of the support rigidity test of the ballast under non-side limit conditions, the load control was adopted in the trial process, and the peak value of load was set to 35 KN [16]. The results of vertical loading-unloading trial of the polyurethane-mixed ballast and common ballast are shown in Figs. 3 and 4 respectively.

As can be seen from Figs. 3 and 4, there is a big difference in the vertical loading-unloading curves between the polyurethane-mixed ballast and the common ballast. From the view of energy, the area enclosed by the loading curve and the displacement axis is the energy conducted by the external load, while the area enclosed by the loading-unloading curve represents the energy dissipated inside the medium, and the area enclosed by the unloading curve and the displacement axis represents the energy released by the medium. In Figs. 3 and 4, the gray part is the energy dissipated inside the ballast, and the yellow part is the energy released by the ballast. The comparison shows that the polyurethane-mixed ballast dissipates larger energy while the common ballast releases larger energy, which indicates that the polyurethane-mixed ballast has stronger damping property and the common ballast has better elasticity.

2.2. The evolution of macro energy

Due to the bond effect of polyurethane, interaction between ballast particles becomes more complex, and the energy composition and evolution law of the polyurethane-mixed ballast under the external load will be different with the common ballast. Jiang et al. [13] and Cheng et al. [17] studied the energy dissipation mode of the particle system. The energy state of the polyurethane-mixed ballast could be described with the first law of thermodynamics, as shown in Eq. (1).

$$\Delta W = \Delta E_s + \Delta E_d + \Delta E_f + \Delta E_b + \Delta E_k \quad (1)$$

where ΔW represents the energy increment of external load; ΔE_s represents the strain energy increment, which includes the increments of elastic strain energy ΔE_{se} and viscous strain energy ΔE_{sb};ΔE_d represents the viscous dashpot energy increment; ΔE_f represents the friction energy increment; ΔE_b represents the increment of material cracking and crushing energy; ΔE_k represents the kinetic energy increment.

In the field test, the loading-unloading process of the polyurethane-mixed and common ballast was conducted uniformly and slowly, which was under the quasi-static loading condition, so the increase of kinetic energy of ballast particles

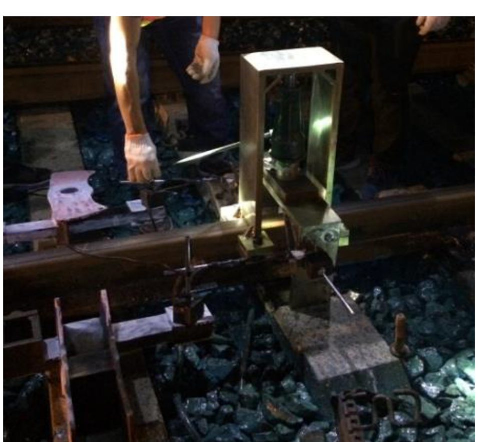

Fig. 1. Trial of the polyurethane-mixed ballast.

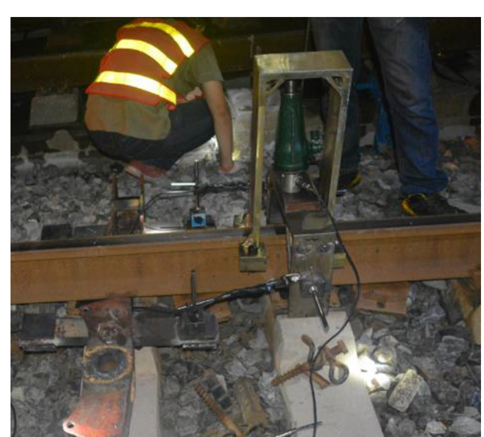

Fig. 2. Comparative trial of the common ballast.