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Development of quick-hardening infilling materials for composite railroad tracks to strengthen existing ballasted track

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A B S T R A C T

A composite railroad track is a rigid track system that is developed using quick-hardening infilling materials, and has the advantages of a reduced maintenance cost compared to a conventional ballasted track. Quick-hardening infilling materials were developed in this study, which does not require the processes of cleaning the aggregates crushed due to the repeated load imposed by rolling stock, and thus the materials can strengthen existing ballasted tracks with an enhanced level of efficiency and speed. Theoretical reviews of pore size, permeability, pore channel length and tortuosity depending on the size of the aggregate in ballasted tracks were conducted first to predict the influence of filling parameters of infilling materials for composite railroad tracks. Based on the theoretical filling performance analysis of ballasted tracks, a thermosetting polymer was developed, which is a 3D cross linking agent that performs redox radical polymerization reaction at room temperature. The polymer was used as a primary filling material to fill the lower ballast layer, which could not be filled by conventional cement-based filling materials. A double-layered composite was formed by filling the upper ballast layer with the ceramic-based secondary filling material using the reaction between dead-burned magnesia and acid ammonium phosphate. The performance of infilling materials was validated through strength measurement and microscopic analysis.

1. Introduction

The ballasted railroad track has long been used worldwide as a standard track structure because of its ease of maintenance and low construction cost, as well as its suitability for high-speed trains. However, since ballasted tracks tend to gradually deteriorate due to repeated train load, continuous maintenance is required to reduce settlement and track irregularities.

The elasticity of a ballasted track is reduced with the increase in the amount of abraded fine particles due to gravel friction, as the ballasted track is affected by the repeated and/or impact loads caused by train running [1]. Moreover, porosity is reduced commensurate with the increase in fine particles and saturated water in the track, which further reduces the elasticity of the track. The moisture and moisture-containing particles are consolidated upward, causing the disturbance of sleepers [2,3]. This vulnerability of the ballasted track may lead to low ride comfort, high risk of derailment and reduction in service. As a traditional ballasted track has the problems described above, regular ballast cleaning or replacement is required, which entails a huge maintenance effort and cost, including labor–intensive processes. Furthermore, additional maintenance costs are involved as track capacity and train speed increase. As the way to deal with such requirements, concrete railroad track that requires very little maintenance has been increasingly adopted [4,5].

To reduce the maintenance effort involved in conventional ballasted track, methods of converting ballasted track into concrete track using rapid-hardening mortar have been developed [6–9]. The quick-hardening concrete track used for a conventional ballasted track uses prepacked concrete technology through filling cement mortar into the voids of gravels. Prepacked concrete is an in-situ method of injecting cement-based grout including admixture to fill the voids after placing coarse aggregate into the form [10,11]. A rapid-hardening and highly flowable cement mortar that could be hardened for use in 3–4 h to reduce the operational suspension has been developed by multiple researchers [6–9]. In this system, however, it is necessary to remove contaminated

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gravel for cleaning in order to secure the adhesion between gravel and mortar. It is because interfacial bonding strength is critical to ensure strength of materials level [12–15]. In order to use conventional cement-based infilling materials, a waterproof cloth shall be laid to reduce the flow loss of cement mortar prior to laying the clean gravel. After laying and tamping the gravel, a stabilization process by rolling stock for 20–30 days is needed, and cement mortar injection and curing processes shall follow before train operation [6–9]. Since the aforementioned process requires about 30 days, the process needs to be enhanced both in terms of schedule and cost.

The aim of this research is to develop the quick-hardening infilling materials to form composite railroad tracks by injecting into the ballast layer without the process of cleaning the aggregates on the existing ballasted track within the limited non-operation time (2–3 h). To the best of the authors' knowledge, no attempt has previously been made to develop chemical infilling materials for railroad tracks in unfavorable conditions with uncleaned aggregates and abraded fine particles. For effective filling, a theoretical review of porosity, pore size, pore channel length and tortuosity with different aggregate particle sizes was conducted. Based on theoretical calculations, two types of infilling materials were developed separately based on the characteristics of two designated layers. In addition, microscopic analysis of composite specimens was carried out to validate the filling performance of infilling materials and theoretical calculations.

2. Analytical investigation of the requirements for infilling materials

While the infilling of cement mortar is generally performed by using gravity infilling or injection, the former is usually adopted for hardening the existing ballasted track for practical reasons [16]. In gravity infilling, the flowability of infilling materials is a very critical factor for effective filling into the voids of aggregates. A theoretical review is carried out to understand the effects of particle size and distribution on effective filling, by considering porosity, pore size, pore channel length and tortuosity.

2.1. Prediction of porosity

The prediction of the porosity of ballast tracks should be considered as an important factor in developing an infilling type composite track system. When aggregate particle size is d_p and the size of the bed on which the aggregates are arranged is D_r, Furnas [17] proposed the following equation for experimental statistical porosity (φ):

$$\varphi = 0.375 + 0.34\frac{d_p}{D_r} \tag{1}$$

Considering the fact that the design specification of aggregate size distribution in ballasted track is 22.4 mm–63 mm, porosity of the ballast with the smallest particle size of 22.4 mm is 38.3%. Should the ballast be crushed to fine particles by abrasion over time, the porosity of the particles with diameters of 1 mm or less is 37.5%, which could cause a pressure loss of 11.2–14%, and thus no significant injection resistance is estimated.

2.2. Prediction of pore size

Moldrup et al. [18] proposed the following experimental equation on pore size formed on aggregates on bed:

$$d_{pore} = \frac{2}{3}\frac{\varphi}{(1-\varphi)}d_p \tag{2}$$

Considering the particle size distribution is 22.4–63 mm, pore size of the ballast with the smallest particle size of 22.4 mm is 9.25 mm. However, pore size of fine particles is theoretically estimated as 0.4 mm when particle size is reduced to 1 mm or less because of deterioration over time, and thus injecting cement mortar-based infilling material would cause problems.

2.3. Pore channel length and tortuosity

Scheidegger [19] proposed the experimental equation for the length of pore channel linking aggregate pores and route deflection and tortuosity, which is intended to identify the route length of infilling materials and flow loss by tortuosity. The tortuosity (τ), when ballast thickness is L and mean pore length is L_e, can be estimated using the following equation [19]:

$$\tau = \frac{L_e}{L} \tag{3}$$

Boudreau [20] proposed an experimental equation on porosity and tortuosity (τ) using Scheidegger's experiments as follows:

$$\tau = \sqrt{1-\ln\left(\varphi^2\right)} \tag{4}$$

Therefore, tortuosity (τ) of regular ballasted track can be estimated as 1.70 using Eq. (4). In the case of an $L = 300$ mm ballast using Eq. (3), pore channel length (L_e) is estimated as 511.4 mm, which indicates that a complete filling can be made when infilling materials flow to 511.4 mm.

2.4. Permeability

The Kozeny–Carman equation has been widely used to derive the permeability as a function of the characteristics of the soil medium [21–23]. By assuming laminar flow of porous medium, permeability (k) for general cases can be calculated as follows [24]:

$$k = \frac{d_p^2\varphi^3}{180(1-\varphi)^2} \tag{5}$$

Considering particle size distribution in ballasted track, permeability of the ballast with the smallest particle size of 22.4 mm is 0.410. Should the ballast be crushed into fine particles over time, permeability of particles sized 1 mm or less is 7.53×10^{-4} and penetration filling of cement-based mortar would be almost impossible.

Through reviewing the rheological conditions necessary for filling performance of infilling materials to ballasted tracks, it was found that infilling using quick-hardening high flowable cement-based mortar would be possible if the ballast consists of standard sized aggregates. However, cement-based infilling materials would be difficult to use where the porosity of ballast tracks has been substantially reduced due to deterioration of the ballast over time. Accordingly, infilling methods using cement-based materials require the process of cleaning the old ballast to eliminate the crushed particles.

3. Development of chemical infilling materials for composite railroad tracks

To accomplish the goal of this experimental research, an attempt is made to develop chemical infilling materials that would be able to overcome the infilling limit of cement-based mortar. After prime