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Effect of gradation of aggregate and size of fouling materials on hydraulic conductivity of sand-fouled railway ballast

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HIGHLIGHTS

- Hydraulic conductivity of ballast was investigated by large-scale permeability test.
- Permeability of ballast was compared for different initial gradations.
- Effect of coarse and fine-grained sand on permeability of fouled ballast was evaluated.
- Permeability of ballast was determined for both laminar and turbulent flow condition.
- Power law can better characterize the water flow through clean ballast.
- Nonlinear relationship is observed for water flow through fouled ballast with coarse sand.

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ABSTRACT

Contamination of ballast due to penetration of sand into the voids between ballast aggregate adversely affects the drainage potential of the track structure in desert areas. Using finer gradation with less uniformity for initial gradation of clean ballast aggregate can lead to more reduction in the permeability of sand-fouled ballast. Furthermore, water flow through clean ballast can be different from the flow regime through contaminated ballast due to change in porosity. The present study evaluates the effect of initial gradation of ballast aggregate and fouling materials (including coarse-grained and fine-grained sand) on hydraulic conductivity of railway ballast by establishment of both laminar and turbulent flow conditions. For this purpose, a series of large-scale constant head permeability tests is conducted on different gradations of clean ballast as well as contaminated ballast samples with various ratios of fouling materials. According to the experimental results, more uniformity of gradation of clean sample leads to higher values of hydraulic conductivities. In addition, establishment of nonlinear relationship based on the power law between the discharge velocity and hydraulic gradient can better characterize the water flow through clean ballast as well as fouled ballast samples contaminated by coarse sand. Finally, it is concluded that the permeability of contaminated ballast samples with various initial gradation is approximately the same for high fouling ratios.

1. Introduction

Ballast layer as sleeper support is a conventional railway track structure to transmit the train load into the underlying base courses as well as to drain water outward the track structure. Fresh crushed ballast mainly comprises of coarse angular aggregate with high uniformity. Ballast fouling is an important problem in the ballasted railway tracks caused by both aggregate degradation and external contamination [33]. Selig and Waters [30] categorized ballast fouling from various sources including degradation of ballast aggregate, penetration of fine particles from underlying layers, permeation of external materials from the surface of the track (such as sand), and erosion around the sleepers.

Ballast fouling influences the mechanical response of ballast materials by decreasing the shear strength of this layer and consequently reducing the stability of the railway track structure. In previous researches, adverse impacts of fouling on the mechanical behavior of ballast were characterized by considering various fouling materials [14,16,18,8].

Contamination of ballast affects the physical properties of ballast materials such as the permeability of ballast layer. Fouling leads to the reduction in the rate of percolation of water through

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the coarse aggregate layer due to filling the air voids with fine particles. In this relation, Parsons [24] carried out a series of large-scale permeability test on ballast to assess the drainage of track substructure. Tennakoon et al. [34] measured the hydraulic conductivity of contaminated ballast samples with different fouling materials. Their observations showed that the hydraulic conductivity of fouled ballast is close to the permeability of fouling materials for high amounts of contamination. In research carried out by Rahman et al. [26,27], a large-scale box was manufactured to conduct the constant head permeability as well as soil resistivity tests on clean and contaminated ballast samples. In general, higher fouling ratio led to less ballast resistivity due to existence of water. Parsons et al. [25] showed the validity of resistivity test for evaluation of the amount of ballast fouling by performing large-scale tests. Paiva et al. [23] assessed the permeability of fouled ballast sample by conducting permeability tests. Measured values for the hydraulic conductivity of the fouled ballast were significantly less than the hydraulic conductivity of clean ballast.

Ballast layer experiences a high level of fouling in desert areas resulting from filling voids between coarse aggregate with fine-grained sand. This phenomenon leads to increasing the stiffness of this granular layer and consequently the foundation coefficient of support. In this relation, [35] characterized different strategies for the renovation of ballasted tracks in sandy and dry areas. In another research work, the effect of sand-fouled ballast on maximum bending moment in concrete sleepers was assessed by conducting field tests [36]. Also, Esmaeili et al. [9] evaluated the vibration of track from passing train in the case of sand-fouled ballast. The observations showed that increase in fouling amount results in higher values of maximum induced acceleration and less values of maximum displacement. In addition, Su et al. [32] carried out a series of constant head permeability tests on the railway ballast to determine the relationship between the hydraulic conductivity and the fouling ratio by using fine sand and coarse sand as fouling materials. Obtained results indicated that the hydraulic conductivity of contaminated ballast samples approaches to the permeability of fouling materials.

Generally, Darcy's law was employed in previous researches to determine the permeability coefficient of ballast materials by assuming a linear flow. Assuming laminar flow, however, may not be appropriate to measure the drainage capacity of porous materials, and recent studies have indicated that nonlinear flow through pervious granular media was a more reasonable mechanism. Fwa et al. [10] estimated the permeability of aggregate used for layers of highway pavement by developing a general relationship based on the power law. In the research work carried out by Ghabchi et al. [13], the proposed power law was applied on laboratory permeability tests to assess the influence of particle size distribution, angularity and surface roughness on the permeability of granular base courses. In addition, Chandrappa et al. [6] observed nonlinear flow through pervious concrete mixtures by conducting falling head permeability tests using various hydraulic heads. Furthermore, Sedghi-Asl et al. [29] evaluated the flow regime through packed granular materials by calculating the Reynolds number based on the diameter of the particles. Generally, it was found that increasing the hydraulic gradient leads to turbulence of flow and consequently estimating higher values of Reynolds number.

The effects of initial gradation of clean ballast as well as the size of fouling materials on the permeability of sand-fouled railway ballast have not been well established in previous researches. It is also not clear whether the flow condition through ballast material is linear or nonlinear. As such, the main purpose of the present study is to assess the hydraulic conductivity of clean ballast samples with various initial gradations as well as ballast contaminated with various ratios of coarse-grained and fine-grained sand. This study also investigates flow conditions through ballast material to determine whether linear or nonlinear flow regime persists. A series of the laboratory tests are carried out to simulate drainage conditions of sand-fouled railway ballast (specifically fine sand) in desert areas and to evaluate the role of ballast aggregate gradation on the hydraulic conductivity of fouled ballast material.

2. Methodology

The present study characterizes the hydraulic conductivity of railway ballast fouled with coarse-grained and fine-grained sand by allowing both linear and nonlinear flow conditions through tested specimens. For this purpose, a series of large-scale constant head permeability tests are conducted on clean ballast samples with different gradations as well as fouled specimens with various ratios of fouling. Contaminated ballast is produced by adding sand to the clean aggregate samples. Table 1 presents physical properties of considered ballast materials as well as rounded river aggregate. Fig. 1 shows different gradations used for clean ballast samples along with the gradation of coarse sand and fine sand as fouling materials. Also, the gradation properties of considered particle size distributions for clean ballast samples are included in Table 2.

3. Large-scale constant head permeability test

To determine the hydraulic conductivity of clean and fouled ballast samples, a large-scale constant head permeability test apparatus was manufactured (Fig. 2). The apparatus consists of a cylindrical chamber made of fiberglass with dimensions of 460 mm diameter and 720 mm height. The ballast sample subjected to water flow is 450 mm in diameter and 300 mm in height. A large diameter specimen is used to minimize the effects of boundary conditions. Using 300 mm thickness of the sample characterizes typical thickness of the ballast layer in the field [15,17]. A discharge pipe located 150 mm above the top of the ballast sample maintains constant head at all times. Also, a 50 mm pipe and valve at the bottom of the chamber allows control of flow of water upward through the sample during the test and water outlet after the test. A large water reservoir with diameter of 850 mm and height of 1190 mm is used to control water head. Fig. 3 illustrates clean ballast sample inside the cylindrical chamber.

Each permeability test requires approximately 3 h to complete. Each specimen is first saturated for 24 h, prior to conducting the permeability test. During the permeability test, water is allowed to move through the saturated ballast sample and the discharged water is collected over a time period. Water levels are maintained in the reservoir and in the cylindrical chamber containing the ballast sample to provide constant head permeability test conditions. After changing the head, differential measurements are taken when water levels become stable. The procedure is repeated for various head differentials applied on ballast sample.

In the present study, the fouling ratio (FR) used to quantify the amount of contamination of ballast, is computed as follows:

$$FR = \frac{M_F}{M_B} \times 100 \quad (1)$$

FR = Fouling ratio (%)
M_F = Dry mass of the fouling material finer than 9.5 mm size (kg)
M_B = Initial dry mass of the clean ballast sample (kg).

Fig. 4 illustrates ballast samples fouled with coarse and fine sand for different values of fouling ratios.