Construction and Building Materials 145 (2017) 117–125

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

An experimental study on the characteristics of polyurethane-mixed coarse aggregates by large-scale triaxial test

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HIGHLIGHTS

- This paper focuses on the behavior of ballast aggregates induced by train loading. To improve performance of the ballast, polyurethane is added. The moduli and strength are investigated according to content of polyurethane.
- A large scale triaxial testing equipment was applied to evaluate the behavior of ballast accurately. The large triaxial tests lead to the correlation between polyurethane content and stiffness of polyurethane mixed ballast. The large scale triaxial tests provide with predictive model for strength as well.
- These simple models are believed to help design the ballast with polyurethane without expensive and cumbersome testing.

ARTICLE INFO

Article history:
Received 14 March 2016
Received in revised form 5 October 2016
Accepted 12 March 2017

Keywords:
Polyurethane
Ballast
Stiffness
Strength
Predictive equation
Performance
Coarse aggregates

ABSTRACT

The two main functions of ballast are train-load distribution and track-water drainage. Repeated train passage subjects ballast aggregates to abrasion and, eventually, breakage. Mixing of bonding materials such as polyurethane into aggregates can effectively mitigate ballast degradation. In the present study, large-scale triaxial tests were carried out to investigate the characteristics of polyurethane-mixed ballast materials. The stiffness and strength of the materials could be predicted in terms of the polyurethane contents, and the linear relationships could be established. According to those relationships, the performance of polyurethane-mixed aggregates as enhanced railway ballast materials can be simply but reasonably estimated.

1. Introduction

Ballast is composed of coarse aggregates ranging generally from 20 to 62 mm in size. Easy maintenance and elastic behavior mean that ballast systems have been widely utilized. However, increasing traffic volume, speed, and weight lead to the necessity of frequent ballast maintenance. Additionally, frequent ballast maintenance involving, for example, tamping, accelerates the deterioration of ballast materials due to aggregate breakage. Fouled ballast (e.g., fine aggregates) usually is linked to poor performance [15]. Such ballast, for example, prevents infiltrated rainwater from draining. In fact, Gidel et al. [6], Ekblad [5], and Werkmeister et al. [16] identified entrapped water as one of the major causes of irregular settlement.

There have been efforts to reduce ballast-maintenance time and cost by improving ballast performance. The rapid-hardening method [10] has been proposed and applied to some ballast tracks. It transforms ballast track to concrete track by introduction of liquid cement mortar. But because of a lack of reinforcement, which condition differs from the case of a traditional concrete track, cracks would occur and result, even, in partial failure. Furthermore, with respect to cracking and settlement, maintenance, as is the case with traditional concrete track, will be difficult.

In this regard, a possible alternative for improved ballast performance is polyurethane, especially in vulnerable areas such as transient zones between bridges and earthwork and rail switches and turnouts. Thanks to its high degree of freedom in gel-time and strength, polyurethane can be used effectively for enhanced ballast

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http://dx.doi.org/10.1016/j.conbuildmat.2017.03.107
0950-0618/

elasticity, strength, and durability without any loss of permeability.

Boler (2011) [2] conducted direct shear tests with polyurethane-mixed ballast. Boler showed that polyurethane improved ballast properties including friction angle (from 34.8° to 40.7°) and cohesion (from 97.4 to 271 kPa). Kim et al. [9] evaluated the effect of polyurethane materials on ballast performance (acceleration and settlement) in operating lines, as did Lee et al. [11] and Kang et al. [8]. Woodward et al. [17] introduced polyurethane applications to transition and crossing zones and studied their effects. They found, in a subsequent laboratory-test-based study, that polyurethane increased track stiffness by 40% [12].

Laboratory testing has been commonly employed to evaluate ballast-material properties [14,7,2]. Actual-grain-size of ballast materials, however, are substantially beyond the capacity of most available apparatuses. For this reason, four modeling methods — the scalping method; the parallel grading method; quadratic grain-size distribution curve generation, and the replacement method — have been adopted for ballast behavior estimation according to actual grain size. Whereas the parallel grading method is considered the most effective [13,18–22], it cannot produce exactly the same results as by actual-size of material testing.

In this study, large-scale triaxial tests were performed with both ballast-only and polyurethane-mixed ballasts of different mixing ratios in order to evaluate the effect of polyurethane mixing on the mechanical behaviors of actual ballast materials. It is expected that this paper will provide fundamental information on the behaviors of ballast-only and polyurethane-mixed ballast and, thereby, help maintenance engineers' application of polyurethane-mixed ballast to problematic areas such as transient zones, rail-crossings, and turnouts.

2. Objectives

This study aimed to evaluate the fundamental material properties (i.e., stiffness, strength) of ballast-only and polyurethane-mixed ballast using large-scale triaxial tests. It is expected that the fundamental polyurethane-mixed ballast composite characteristics, thus obtained, will serve as the preliminary findings paving the way to practical polyurethane implementation. Certainly, those characteristics will prove useful to the design and evaluation of polyurethane-mixed ballasts that can provide improved performance.

3. Test program

The applicability and effect of polyurethane on ballast were investigated. The maximum size of aggregate grain tested was 60 mm (see Fig. 2), as this is the maximum utilized by the Korean High-Speed Railroad. In addition to aggregate size, stiffness and strength also were considered in the numerical analysis and design of polyurethane-mixed ballasts. Deformation moduli and strength were investigated using actual aggregates used for ballast materials in Korea.

3.1. Large-scale triaxial test

The large-scale triaxial testing apparatus (see Fig. 1) consists of two actuators, a dynamic actuator of 200 and a static actuator of 2000 kN. The 200 kN dynamic actuator is used for accurate control. The apparatus is equipped with three triaxial cell types of (diameter × height) 500 mm × 900 mm, 700 mm × 1200 mm, and 900 mm × 1650 mm, respectively (see Fig. 2). These triaxial cells are waterproof and pressure-resistant up to 2 MPa for measurement of both compressive and tensile forces. A triaxial cell of 500 mm × 900 mm was used for ballast-only testing in the 2 mm/min displacement-controlled loading mode.

3.2. Testing materials

3.2.1. Ballast aggregates

The aggregates used in this study and their grain size distribution (gradation) are shown in Fig. 2. The clean ballast (i.e., intact ballast materials) met the ballast-gradation criteria (Korean Standard for Railway Design, 2011; red dotted lines in Fig. 2); however, the polyurethane was not applied to clean ballast but to problematic ballast with which settlement and/or other ballast-related issues would be likely to occur. Problematic ballast materials are ballast aggregates that are broken and thus contain more fine particles than clean ballast; this meant that in the present study, the gradation was finer than the lower limit of the criteria (see Fig. 2).

The ballast materials utilized in this study were transported from the same quarry as has supplied ballast materials to the Korean High-Speed Railroad. Also, the same gradation was used for both the ballast-only tests and polyurethane-mixed ballast tests in evaluating the effect of polyurethane on ballast behavior.

3.2.2. Polyurethane material

Polyurethane is formulated by chemical reaction of isocyanate compound with hydroxy compound. It can be classified into hydrophilic, hydrophobic, and elastometric materials based on their reaction with water and their elongation. The key feature of polyurethane is the control it affords over its curing time (gel-time) and strength according to the purpose of its use. XiTRACK [17] and Elastotrack [4,3] are the two representative polyurethane materials used for the purpose of improved ballast track.

Its two constituent materials are mixed in a hose and injected into ballast, during which time it is hardened. The gel-time is approximately ten seconds, and 90% of the target strength is achieved in one hour. XiTRACK partially fills the voids among ballast aggregates, thus maintaining both permeability and the ballast track's capacity to support train loads.

Elastotrack is composed of isocyanate and resin. Its gel-time is around 30–60 min, and is adjustable according to the mixing ratio of its constituents. Its strength gradually increases as its materials harden. Elastotrack also partially fills the voids among ballast aggregates, and additionally enables ballast recycling.

These widely used polyurethanes, however, are expensive; therefore, a new and more economical polyurethane material, ERSBallast, was developed in Korea. ERSBallast has similar characteristics to XiTRACK in gel-time and strength, but the injection method is different. Whereas XiTRACK is injected from the surface of the ballast, thus requiring larger amounts of materials than are necessary for support of train loads, ERSBallast is designed to be injected considering the ballast pressure distribution induced by train loading. In other words, ERSBallast is injected into load-transferring areas where train loads are directly applied, in order to increase ballast performance and, at the same time, reduce polyurethane-material usage. This injection method currently is being investigated through laboratory testing and numerical analysis.

In the present study, ERSBallast was used to evaluate the effect of polyurethane on ballast behavior and suggest ballast design improvement in the basic mechanical properties. Stiffness of ERSBallast used in this study is approximately 24 MPa.

3.3. Sample fabrication

Ballast-only samples and polyurethane-mixed samples were prepared and tested in order to evaluate the effect of developed polyurethane materials (i.e., ERSBallast).