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EFFECTS OF BALLAST DEGRADATION ON PERMANENT DEFORMATION BEHAVIOR FROM LARGE-SCALE TRIAXIAL TESTS

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ABSTRACT

Consisting of large sized aggregate particles with uniform size distribution, ballast is an essential component of the track substructure to facilitate load distribution and drainage. As freight tonnage accumulates with traffic, ballast will get fouled increasingly due to either aggregate breakdown and degradation or contamination by other materials such as coal dust and subgrade soil intrusion. Fouling affects shear strength and load carrying ability of ballast layer especially under wet conditions. According to Selig and Waters [1], ballast fouling is often due to aggregate degradation, which covers up to 76% of all the fouling cases. To investigate the effects of ballast aggregate breakdown and degradation on the mechanical behavior of fouled ballast, a series of Los Angeles abrasion tests were performed in this study to generate fouled ballast materials caused by particle breakage and abrasion under a well-controlled laboratory environment. The change of particle shape properties during the Los Angeles abrasion tests was quantified and studied through image analysis technology. Large-scale triaxial tests were performed on specimens of new ballast, degraded ballast coarse particle fraction (without fines), and full gradation of degraded ballast (with fines) under repeated load application using a triaxial test device recently developed at the University of Illinois specifically for ballast size aggregate materials. The large-scale triaxial results indicated that the specimen having those degraded coarse particles yielded higher permanent deformation trends from repeated load triaxial testing when compared to the specimen with the new ballast gradation. As expected, the highest permanent deformation was obtained from the degraded ballast specimen having fine particles and the Fouling Index (FI) value of approximately 40.

INTRODUCTION

The purpose of ballast is to provide drainage and structural support for the loading applied by trains. As ballast ages, it is progressively fouled with materials finer than new ballast sized aggregate particles. Fine or fouling materials are commonly generated from the ballast aggregate breakdown and outside contamination (e.g., coal dust from coal trains or from subgrade soil intrusion). Previous research studies reported that the main cause of ballast fouling was the degradation and breakdown of the uniformly-graded large ballast particles under repeated traffic loading [2, 3]. Selig and Waters [1] concluded that up to 76% of the ballast fouling was due to ballast breakdown, in other words, ballast degradation. In accordance, to quantify ballast fouling conditions, Selig and Waters [1] proposed two indices: (i) Fouling Index (FI) and (ii) Percentage Fouling. Fouling Index (FI) is the summation of percentage by weight of ballast material passing the 4.75 mm (No. 4) sieve and the percentage passing the 0.075 mm (No. 200) sieve. Percentage Fouling is the ratio of the dry weight of material passing the 9.5 mm (3/8 in.) sieve to the dry weight of the total sample. In the context of this paper, fine materials are those with particle sizes less than 9.5 mm or passing 3/8-in. sieve.

Increased ballast settlements were reported by researchers when the amount of fouling material in ballast increased [4-6]. Because ballast degradation is the main reason leading to ballast fouling and few related studies were found in the literature, this study investigates the effect of ballast degradation on permanent deformation behavior from large-scale triaxial tests. A series of Los Angeles abrasion tests were performed in this study to generate fouled ballast material caused by particle degradation under a well-controlled laboratory environment. Large-scale triaxial tests were performed on the new ballast and degraded ballast specimens. The triaxial testing efforts focused on (i) the effects of gradation considering those finer materials, i.e. particles less than 9.5 mm (3/8 in.), generated through ballast degradation and (ii) the effects of aggregate shape properties, such as angularity and flatness and elongation, for particles larger than 9.5 mm (3/8 in.). Accordingly, triaxial tests were also performed on those aggregate particles still found to be larger than 9.5 mm (3/8 in.) in size after the LA abrasion tests. This fouled ballast coarse fraction would constitute the skeleton of an in-service ballast layer in the field.

Permanent deformation results of both the new and fouled coarse aggregate fraction of fouled ballast specimens (FI=0) as well as the fully fouled (FI=40) ones are presented in this paper. The experimental study results indicate that the specimens having those degraded particles larger than 9.5 mm (3/8 in.) only yielded higher permanent deformation trends from repeated load triaxial testing when compared with the original new ballast gradation. The highest permanent deformation trend was obtained from the degraded ballast specimen having the finer materials, i.e. particles less than 9.5 mm (3/8 in.), and the fouling index value of approximately 40. This shows that the large aggregate skeleton of the degraded ballast specimen had finer materials in excess of just filling the voids but instead, the finer materials established a weak load carrying matrix that compromised aggregate particle to particle contact.

TEST EQUIPMENT AND MATERIAL

Los Angeles (LA) Abrasion Test and Image Analysis

The ballast material used in the laboratory was a 100% crushed limestone, which adequately met AREMA No. 24 gradation requirements. Approximately 10 kilograms of clean ballast materials were placed in the LA abrasion drum (see Figure 1) together with 12 steel balls, which are typically used in the LA abrasion test (AASHTO T 96 or ASTM C 131).

The drum was set to rotate on the average 50 turns per minute and for a total drum turns of 1,500 times to reach the fully fouled condition with a Fouling Index (FI) of 40. After finishing 1,500 turns, the drum was allowed to stand still for 10 minutes to let dust settle before the tested material was poured out. In order to minimize loss of fine materials, both the inside of the drum and the steel balls were carefully hand brushed after the test. All particles above 25.4 mm or 1.0 in. sieve were also brushed to collect dust and fine material before sieving. The outlined procedure was repeated until enough materials were generated for conducting large-scale triaxial tests and all the generated degraded ballast material were evenly mixed before preparing the triaxial test specimens. Further details on generating degraded ballast material through LA abrasion tests have been provided elsewhere [7]. The gradations of clean and degraded ballast specimens (after 1500 turns of LA abrasion test) are shown in Figure 2. Another gradation curve, which represents the gradation of the large particles (coarse fraction) only, is also given in Figure 2. The specimen of the degraded ballast after the LA abrasion testing excluded in that case particles smaller than 9.5 mm or 3/8 in. size.

Figure 1. Photo of Los Angeles (LA) abrasion test equipment

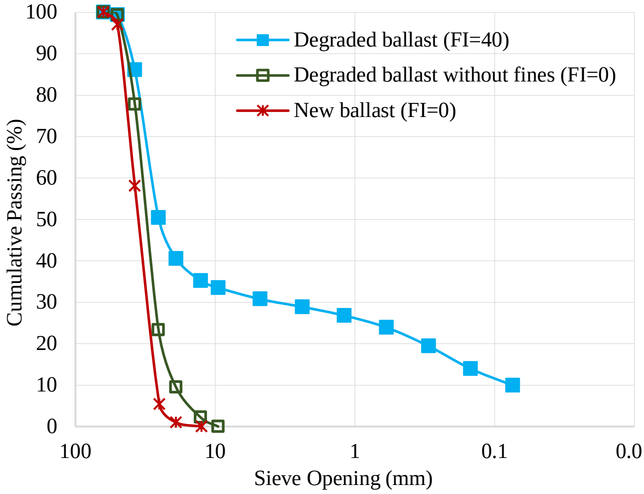
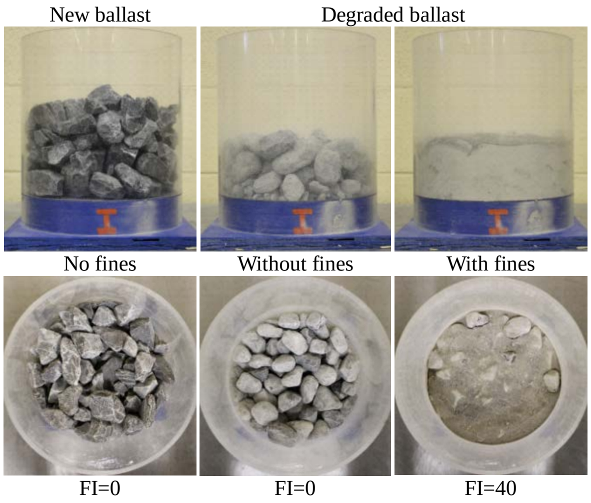


Figure 2. Gradation of ballast materials before/after degradation

It is not obvious how to relate gradation information to ballast layer functional characteristics and the governing mechanisms that would impact ballast layer structural and drainage behavior. To investigate particle contact and particle packing characteristics before and after degradation, approximately 10 kilograms of ballast material obtained from the before and after 1,500 turns in LA abrasion tests were poured into an acrylic chamber with dimensions of 25.4 cm (10.0 in.) in diameter and 25.4 cm (10.0 in.) in height. Figure 3 presents the side and top views of aggregate packing photos taken before and after degradation with the corresponding FI values. Photos of the degraded ballast without fines are also shown in Figure 3 for comparison. It is clearly seen that after 1,500 turns, the same weight (ten kilograms) of degraded ballast occupied less volume as compared to the new ballast in the acrylic chamber. However, for the same weight of degraded ballast, the specimen height remained nearly the same with or without fine particles as shown in Figure 3. Basically, the fine particles generated during degradation occupied the voids created by the large particles. As FI approached 40, nearly all the voids created by the large particles were filled with fine particles.



Fines: Passing 9.5-mm or 3/8-in. size

Figure 3. Photos of side and top views of aggregate packing

Besides the grain size distribution, aggregate shape properties, especially the flat and elongated (F&E) ratio, the angularity index (AI), and the surface texture (ST) index, are key indices quantified by the University of Illinois Aggregate Image Analyzer (UIAIA) [8]. After the LA abrasion tests, aggregate particles larger than 9.5 mm or passing 3/8-in. sieve were hand collected to conduct image analyses using the recently enhanced University of Illinois Aggregate Image Analyzer (E-UIAIA) (see Figure 4) to quantify the shape property changes of ballast particles after degradation. Details of image analyses of aggregate particle shapes before and after the LA abrasion tests can be found elsewhere [7]. These shape indices can also be used in the future as the essential morphological data to generate ballast aggregate particle shapes as 3D discrete elements for a currently developed ballast DEM model.

Repeated Load Triaxial Testing

A large scale triaxial test device has recently been developed at the University of Illinois for testing specifically ballast size aggregate materials (see Figure 5). An internal load cell (Honeywell Model 3174) with a capacity of 89 kN (20 kips) is placed on top of the specimen top platen. Three vertical LVDTs are placed around the cylindrical test sample at 120-degrees angle between each other to measure the vertical deformations of the specimen from the three different side locations. Other details about the large-scale triaxial test device have been provided elsewhere [9].

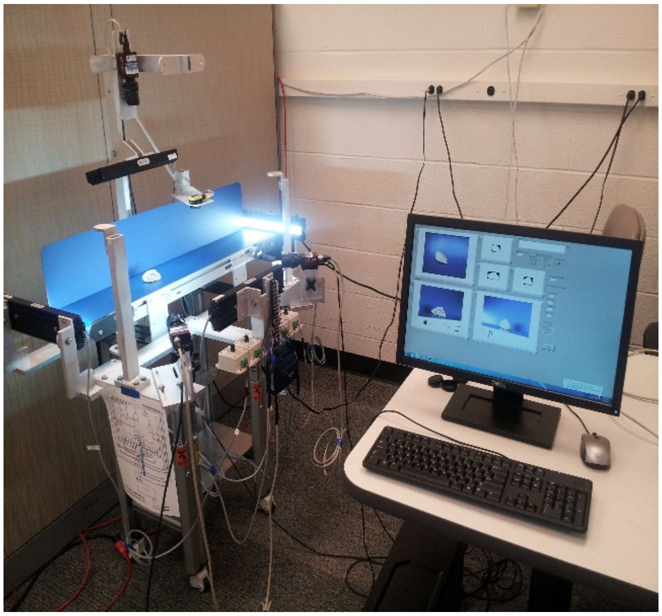


Figure 4. Photo of Enhanced University of Illinois Aggregate Image Analyzer

Figure 5. Photo of University of Illinois Ballast Triaxial Tester

To evaluate permanent deformation characteristics of the ballast materials obtained before and after LA abrasion tests, a realistic field train loading dynamic pulse with 0.4-second load duration and 0.6-second rest period between two pulses was selected. The peak deviator stress applied on the specimen was 165 kPa (24 psi) and the confining pressure was 55 kPa (8 psi). Figure 6 shows the details of the loading pulse used in this study.

The tested ballast specimens were prepared by compacting ballast materials in four lifts. The appropriate amount of ballast material was prepared carefully according to the gradation requirements as indicated in Figure 2. Before making the triaxial test specimen, the ballast material was mixed thoroughly and divided into four parts evenly to minimize segregation. The height of each lift after compaction was 15 cm (6 in.), and for each lift the compaction was applied with the same electric jack hammer for 4 seconds to ensure the same compaction energy was applied to all the test specimens for all the different ballast materials. The total weight of the test specimens and the weight of each lift for different ballast materials were predetermined by a trial and error process. The shape properties and triaxial test specimen details are summarized in Table 1.

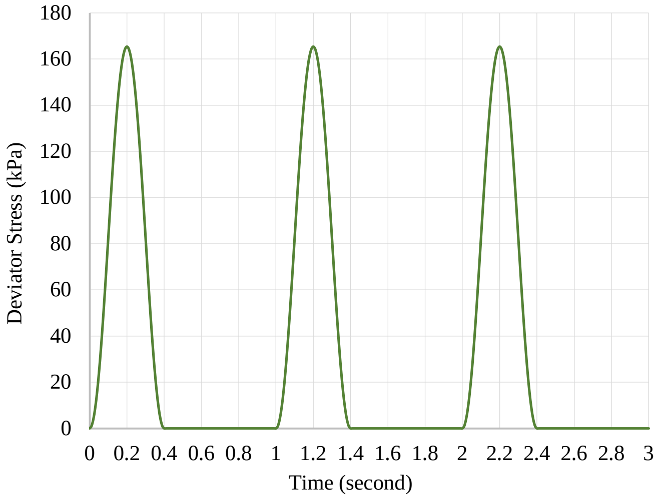


Figure 6. Loading pulse used in repeated load triaxial tests

TEST RESULTS

Figure 7 presents the results of the permanent deformation tests on the new and degraded limestone ballast cylindrical specimens for up to 10,000 cycles. The fully fouled ballast specimen, for which the FI was 40, clearly resulted in the highest permanent axial strain. After 10,000 load cycles, the new ballast specimen had an average permanent strain of 0.62%, while the fully fouled and degraded ballast specimen yielded a permanent axial strain of 1.32%. The specimen of degraded ballast without fines, in other words, the specimen of coarse aggregates fraction of the degraded ballast, gave a permanent axial strain value of 0.92%, which was in between the new ballast and degraded ballast.

Table 1. Triaxial test specimen details and shape properties of large–sized (above 9.5-mm or 3/8-in.) particles

	New ballast	Degraded ballast (without fines)	Degraded ballast (with fines)
Specimen height	61 cm	61 cm	61 cm
Specimen diameter	30 cm	30 cm	30 cm
Specimen weight	70 kg	73 kg	94 kg
Compaction time	16 seconds	16 seconds	16 seconds
Void ratio	0.68	0.61	0.25
Angularity Index (AI)	440	278	278
Flat & Elongated Ratio (FE)	2.3	1.9	1.9
Surface Texture Index (ST)	1	1.3	1.3

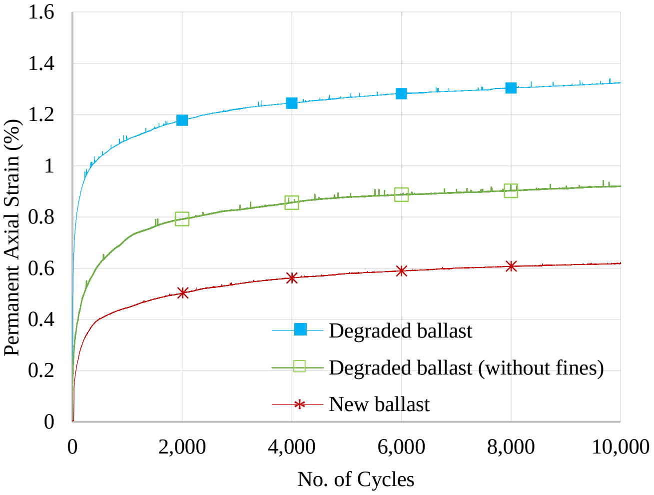


Figure 7. Repeated load triaxial test results for permanent deformation accumulation

The test specimens showed different stress-strain behavior from the initial stage. Significantly different permanent deformations accumulated in the initial stage, while the permanent deformation accumulation rate tended to become similar as the number of loading cycles increased. The difference between the new ballast and coarse aggregates fraction of the fouled ballast is mainly due to the differences in particle shape properties. In other words, no fine fouling materials, i.e., particles smaller than 9.5 mm (3/8 in.), were present in the specimens of these two materials. The coarse aggregates fraction of the fouled ballast had a bit smaller particles (still larger than 9.5 mm) than the new ballast, also indicated by the gradation curve shown in the Figure 2.

However, the aggregate particles were much smoother with lower imaging based AI and ST index values given in Table 1.

The degraded and fully fouled (FI=40) ballast specimens had the highest permanent axial strain among the three different ballast materials. Note that the difference between the degraded ballast and the coarse aggregates fraction was in fact the fouling fine material (particles smaller than 9.5 mm or 3/8 in.) generated during LA abrasion test due to the ballast degradation. These fine materials not only filled the voids but in fact caused loss of contact between large particles in the heavily fouled ballast aggregate skeleton.

CONCLUDING REMARKS

This experimental study investigated the effects of ballast degradation on permanent deformation behavior from large-scale triaxial tests. Los Angeles abrasion tests were performed to generate fouled/degraded ballast materials. Large-scale triaxial tests were then conducted on specimens of new ballast, degraded ballast and coarse aggregates fraction of the degraded ballast. The following conclusion can be drawn from this study:

1. Ballast degradation can cause significant changes of ballast particle shape properties and grain size distributions as compared with corresponding properties of original new ballast materials. As ballast degradation took place in LA abrasion tests, particles tended to be smaller in size and smoother in texture. The specimen with only coarse aggregates (particles larger than 9.5 mm or 3/8 in.) from the degraded ballast yielded higher permanent deformation as compared to the original new ballast specimen. This was mainly due to the smaller particle sizes and how the particles became smoother and more rounded, leading to less stable aggregate interlocking as opposed to the angular particles of the new ballast.
2. Ballast degradation generates fine materials (particles smaller than 9.5 mm or 3/8 in. in size). As ballast degradation took place in LA abrasion tests, voids between large aggregates (particles larger than 9.5 mm or 3/8 in.) were filled by fines. When Selig’s Fouling Index (FI) approached 40, nearly all the voids were filled with fines, which resulted in loss of contact between large particles in the degraded ballast aggregate skeleton. The degraded ballast specimen, which was in heavy fouling condition with FI of 40, had the highest permanent axial strain among the three different ballast specimens.

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