# Effects of Ballast Degradation on Shear Strength Behavior from Large-scale Triaxial Tests

Yu QIAN[a], Erol TUTUMLUER[a,1],
Youssef M.A. HASHASH[a], and Jamshid GHABOUSSI[a]
[a]*University of Illinois at Urbana-Champaign*

**Abstract.** Ballast, typically comprising large sized aggregate particles with uniform gradation, is an essential layer in the railroad track substructure. Functions of ballast include facilitating load distribution and drainage, maintaining track geometry and track stability, and providing track resilience and noise absorption. Throughout its service life, ballast goes through changes in gradation and particle shape properties due to aggregate breakdown/degradation. In United States freight lines, mineral aggregate breakdown/degradation has been reported as the main mechanism causing ballast fouling, which covers up to 76% of all the fouling cases. To investigate the effects of ballast aggregate breakdown and degradation on the mechanical behavior, a series of Los Angeles (LA) abrasion tests were performed to generate fouled materials caused by particle degradation under a controlled laboratory environment. In what follows, large-scale triaxial tests were performed on both clean and heavily fouled ballast specimens using a triaxial test device recently developed at the University of Illinois specifically for testing ballast size aggregate materials. The triaxial testing efforts also focused on (a) the effects of gradation considering those finer materials or fines, i.e. particles less than 9.5 mm (3/8 in.), generated through ballast degradation and (b) 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 only on those aggregate particles still kept after the LA abrasion tests larger than 9.5 mm (3/8 in.) in size, which would constitute the skeleton of the fouled ballast layer in the field. The experimental study results indicated that ballast degradation did not necessarily result in significant strength loss from the monotonic compression tests on dry specimens. On the contrary, in most cases, the dry degraded ballast with or without fines yielded higher strength properties than those observed in the new ballast specimens. Smaller particles provided a "stabilizing" effect that caused a strengthening of the aggregate matrix and accordingly, fines served as a "stabilizer" to fill the voids and increase density in the ballast aggregate matrix.

**Keywords.** aggregate, degradation, fouling, railroad ballast, shear strength, triaxial testing

---

[1] Corresponding Author: Erol Tutumluer, Professor, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, 205 N. Mathews Ave. Urbana, Illinois, USA;
E-mail:tutumlue@illinois.edu

## 1. Introduction

Ballast layer facilitates drainage and load distribution in the railway substructure. As ballast ages, it is progressively fouled with materials finer than new ballast sized aggregate particles. Previous research studies reported that the primary cause of ballast fouling was the degradation and breakdown of the uniformly-graded large ballast particles under repeated traffic loading [1-2]. Based on North American field data, Selig and Waters [3] concluded that up to 76% of the ballast fouling was due to ballast breakdown, also commonly referred to in this paper as the ballast degradation. In accordance, to quantify ballast fouling conditions, Selig and Waters [3] 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. Throughout this paper, fine materials are defined as those with particle sizes less than 9.5 mm or passing the 3/8-in. sieve.

Previous studies reported ballast fouling and degradations to reduce ballast strength especially when the amount of fouling material in ballast increased. Huang et al. [4] conducted a series of large scale direct shear tests using ballast mixed with different fouling agents including coal dust, fine-grained cohesive subgrade soil, and nonplastic mineral filler. Fouling materials were added to compacted clean ballast. Lower shear strength was observed when in general level of fouling increased. Indraratna et al. [5] recently performed large scale triaxial tests on ballast fouled with different proportions of clay. The results indicated that when fouling levels increased, quantified by a newly defined void contaminant index (VCI) accounting for the specific gravities of different fouling materials, the specimen shear strength dropped. Note that the work by Indraratna et al. [5] mainly focused on fouling due to contamination by intrusion materials, such as subgrade soil and coal dust, other than mineral filler generated due to particle breakdown.

Because aggregate breakdown has been the primary cause leading to ballast layer fouling in North American freight lines and relatively few studies can be found in the literature, the recent research focus at the University of Illinois targeted a laboratory investigation of ballast degradation affecting the shear strength behavior through large-scale triaxial testing. A series of Los Angeles (LA) abrasion tests were performed on a clean sample of ballast which caused increased amounts of aggregate particle breakage and abrasion by simply increasing the number of LA test drum turns. Accordingly, ballast materials were generated at different levels of fouling/degradation quantified by Selig's fouling index (FI). Large-scale triaxial tests were then performed on both 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 coarse aggregate fraction of degraded ballast would constitute the skeleton of an in-service ballast layer in the field.

Monotonic shear strength test results of both the new and degraded coarse aggregate fraction ballast specimens (FI=0) as well as the heavily fouled (FI=40) ones are presented in this paper. The experimental study results indicate that particle degradation did not necessarily result in significant strength loss in the fouled ballast specimens when compared to the new clean ballast material. On the contrary, specimens prepared with the dry degraded ballast with or without fines yielded higher strength than the new clean ballast specimen.

## 2. Test equipment and material

### *2.1. 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 above 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 [6].

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 degraded coarse aggregate fraction, is also given in Figure 2. The specimen of the degraded coarse aggregate fraction after the LA abrasion testing excluded in that case particles smaller than 9.5 mm or 3/8 in. size.

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 having 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 case 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.

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

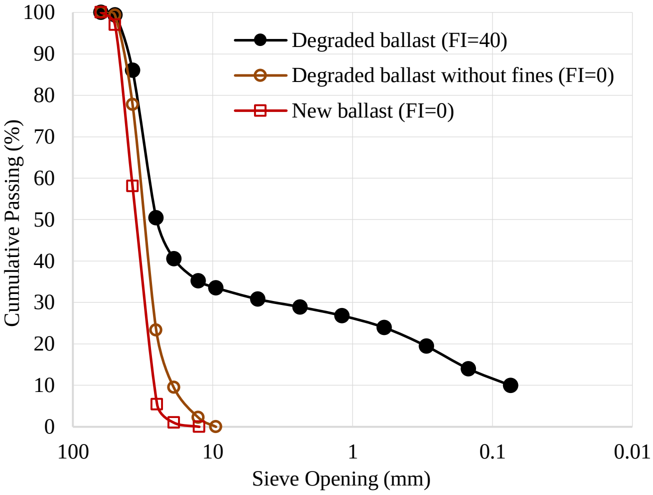
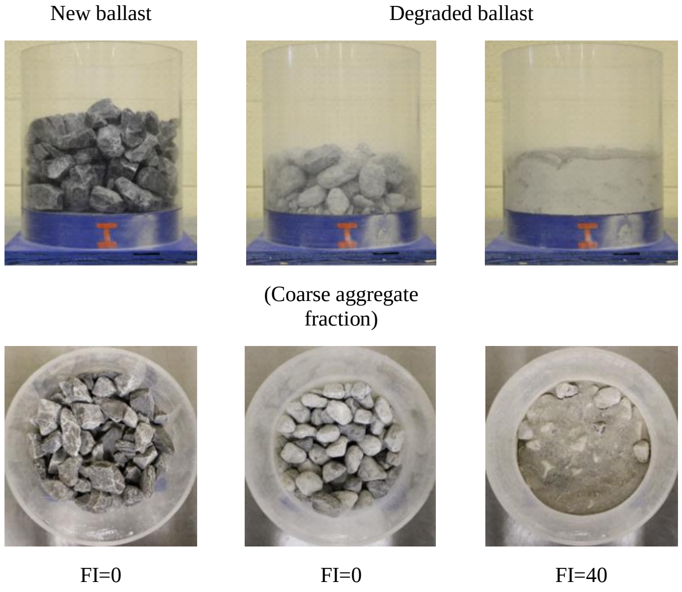


**Figure 2.** Gradation of ballast materials before/after degradation



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

**Figure 3.** Photos of side and top views of aggregate packing [7]

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). 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 [8]. These shape indices have been successfully used as the essential morphological data to generate ballast aggregate particle shapes as three-dimensional (3D) polyhedron shaped discrete elements for a recently developed ballast model for analyzing the assembly behavior using the Discrete Element Method or DEM [9-10].

### *2.2. Monotonic triaxial shear strength 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 [11]. In order to prevent damage to LVDTs due to excessive bulging of specimen during monotonic shear strength test, the axial strain was calculated based on the vertical movement of loading actuator and the LVDTs were not used during the tests.

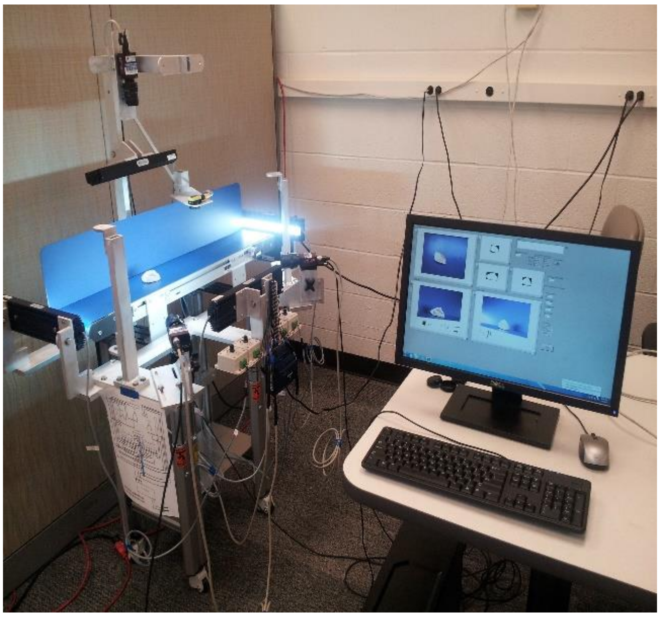


**Figure 4.** Photo of Enhanced University of Illinois Aggregate Image Analyzer

To evaluate shear strength characteristics of the ballast materials obtained before and after LA abrasion tests, a typical loading strain rate of 1%/min, corresponding to 0.1016 mm/s of actuator speed, was selected. All specimens prepared with new clean and degraded ballast materials were loaded up to 10% axial strain at a confining pressure of 69 kPa (10 psi).

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.). For each lift, the compaction applied with the same electric jack hammer was set to 4 seconds to ensure the same compaction energy was applied to all the test specimens in a consistent manner. The total weights of the test specimens and the weights of each lift for different ballast materials were predetermined by a trial and error process. The other details of specimen preparation can be found elsewhere [9]. Table 1 summarizes the aggregate shape properties and the triaxial test specimen details.

**Figure 5.** Photo of University of Illinois Ballast Triaxial Tester

**Table 1.** Triaxial test specimen details and shape properties of different materials

| | **New ballast** | **Coarse aggregate fraction of degraded ballast** | **Degraded ballast** |
|---|---|---|---|
| **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 |

*: average value for all particles retrained by 9.5 mm (3/8 in.) sieve

## 3. Test results

Figure 6 presents the monotonic shear strength test results on the new and degraded cylindrical specimens of a limestone type ballast material for up to 10% axial strain. Interestingly, particle degradation did not result in significant strength loss in the fouled ballast specimens when compared to the new clean ballast material. On the contrary, the preliminary results from this study showed the degraded ballast and coarse aggregate fraction of degraded ballast yielded higher strength than the clean ballast specimen. Comparing the gradations of the three ballast materials (see Figure 2), the coarse aggregate fraction of degraded ballast comprised higher number of smaller particles and was more "well" graded than the clean ballast material, which satisfied AREMA No. 24 uniform gradation specification. The smaller particles within the degraded ballast matrix can potentially help stabilize the aggregate skeleton by minimizing/filling the voids and thus resulting in higher shear strength. Moreover, from the imaging-based shape properties listed in Table 1, particles of the degraded ballast coarse aggregate fraction have significantly lower Angularity Index (AI) values, and also they tend to be more cubical and smoother and hence less susceptible to abrading of sharp corners and edges during strength testing when compared to clean ballast particles. Accordingly, more cubical degraded ballast particles with smoother surfaces can attain a denser packing configuration leading to higher densities for the specimens. This results in higher peak deviator stress values achieved during shear strength testing.

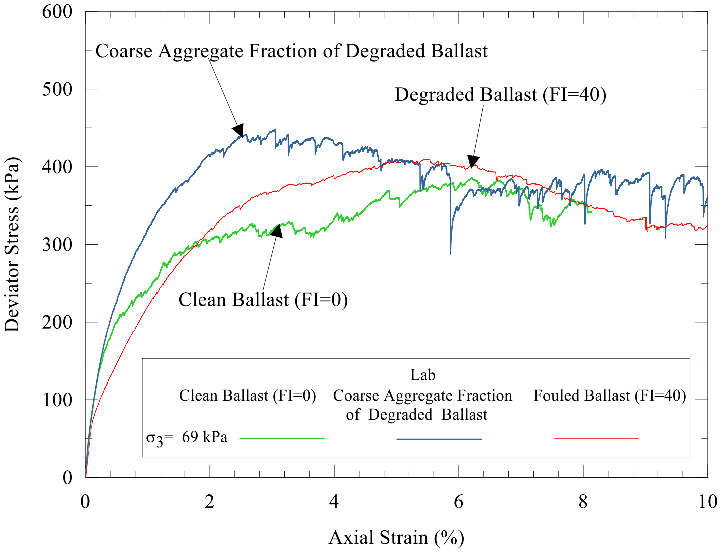


**Figure 6.** Repeated load triaxial test results for permanent deformation accumulation

For the specimens prepared with the degraded ballast, fines (material finer than 9.5 mm or 3/8 in.) filled the voids created by larger particles (see Figure 3), thus helping to stabilize the aggregate skeleton. However, presence of excessive fines in the aggregate matrix results in the loss of contact between large particles, thus making it easier for the large particles to reorient and rearrange. This in turn can lead to significant reductions in the specimen shear strength. The fine particles thus present a "stabilizing" effect in the specimens prepared with the fouled ballast. This could be the reason why degraded ballast (FI=40) had less strength than coarse aggregate fraction of degraded ballast but higher strength than clean ballast. This could also be the reason why the degraded ballast had much smoother stress-strain curves during monotonic shear strength tests. However, all the test results presented here were under dry conditions, i.e., no added moisture was present in the test specimens. Upon introduction of moisture into the specimens, the shear strength behavior of ballast is expected to drop substantially.

## 4. Concluding remarks

This experimental study investigated the effects of ballast degradation on shear strength 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 conclusions can be drawn from this study:

- Ballast degradation can cause significant changes in ballast grain size distributions and particle shape properties when compared to the corresponding properties of the original new ballast material. As ballast degradation took place in LA abrasion tests by gradually increasing the number of drum turns, particles tended to break and become smaller in size and the larger particles left became smoother in texture.

- Based on the preliminary results of this experimental study, ballast degradation not necessarily resulted in significant strength loss from the monotonic shear strength tests. On the contrary, the degraded ballast specimens with or without fines (smaller than 9.5 mm in size or passing the no. 3/8-in. sieve) yielded higher strength properties than the new clean ballast specimens.

- Smaller particles generated during ballast breakdown and degradation could provide a “stabilizing” effect that caused a strengthening of the aggregate matrix by filling the voids created by large particles. Note that fines could also provide a weakening effect in the aggregate matrix by preventing contact between large particles.

## Acknowledgments

This research project was partially supported by the Federal Railroad Administration (FRA) under Contract No. FR-RRF-0033-11-01-00. Mr. James Pforr, former Research Engineer, and Yu Xie, graduate student, at Illinois Center for Transportation (ICT) at the University of Illinois provided considerable help with the laboratory tests. All the support and help are greatly appreciated. The opinions expressed in this article are solely those of the authors and do not represent the opinions of the funding agency.

## References

[1] E. T. Selig, B. I. Collingwood, and S. W. Field. Causes of Fouling in Track, *AREA Bulletin 717*, 1988.

[2] E. T. Selig, V. DelloRusso, and K. J. Laine. Sources and Causes of Ballast Fouling, *Report No. R-805, Association of American Railroads*, Technical Center, Chicago, 1992.

[3] E. T. Selig, and. J. M. Waters. *Track Geotechnology and Substructure Management*, Thomas Telford Publications, London, 1994.

[4] H. Huang, E. Tutumluer, and W. Dombrow. Laboratory Characterization of Fouled Railroad Ballast Behavior. *Journal of Transportation Research Record,* **No. 2117**, (2009), 93-101.

[5] B. Indraratna, N. Tennakoon, S. Nimbalkar, C. Rujikiatkamjorn. Behaviour of Clay-fouled Ballast under Drained Triaxial Testing. *Géotechnique*, **63(5)**, (2013), 410-419.

[6] Y. Qian, H. Boler, M. Moaveni, E. Tutumluer, Y.M.A. Hashash, and J. Ghaboussi. Characterizing Ballast Degradation through Los Angeles Abrasion Test and Image Analysis. *Journal of Transportation Research Record,* **No. 2448**, (2014), 142–151.

[7] Y. Qian, D. Mishra, E. Tutumluer, and H. Kazmee. Characterization of geogrid reinforced ballast behavior at different levels of degradation through triaxial shear strength test and discrete element modeling. *Geotextiles and Geomembranes,* (2015). (in press)

[8] Y. Qian. *Integrated Computational and Experimental Framework for the Assessment of Railroad Ballast Life-Cycle Behavior,* Ph.D. Dissertation, University of Illinois at Urbana-Champaign, 2014.

[9] Y. Qian, S.J. Lee, E. Tutumluer, Y. M. A. Hashash, D. Mishra, and J. Ghaboussi. Discrete Element Method for Simulating Ballast Shear Strength from Large Scale Triaxial Tests. *Journal of Transportation Research Record,* **No. 2374**, (2013), 126–135.

[10] E. Tutumluer, Y. Qian, Y. M. A. Hashash, J. Ghaboussi, and D. Davis. Discrete Element Modeling of Ballasted Track Deformation Behavior. *International Journal of Rail Transportation*, **1(1-2)**, (2013), 57-73.

[11] D. Mishra, H. Kazmee, E. Tutumluer, J. Pforr, D Read, and E. Gehringer. Characterization of Railroad Ballast Behavior under Repeated Loading Using New Large Triaxial Test Setup. *Journal of Transportation Research Record*, **No. 2374**, (2013), 169-179.