LARGE-SCALE, CYCLIC TRIAXIAL TESTING OF RAIL BALLAST

Ali Ebrahimi\textsuperscript{1}, James M. Tinjum\textsuperscript{2}, Tuncer B. Edil\textsuperscript{3}

\textsuperscript{1} PhD Dissertator, Civil and Environmental Engineering, University of Wisconsin-Madison, Madison, WI 53706, e-mail: ebrahimi@wisc.edu
\textsuperscript{2} Assistant Professor, Engineering Professional Development, University of Wisconsin-Madison, Madison, WI 53706, e-mail: jmtinjum@wisc.edu
\textsuperscript{3} Professor, Geological Engineering and Civil & Environmental Engineering, University of Wisconsin-Madison, Madison, WI 53706, e-mail: tbedil@wisc.edu

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Ali Ebrahimi¹, James M. Tinjum², Tuncer B. Edil³

¹ PhD Dissertator, Civil and Environmental Engineering, University of Wisconsin-Madison, Madison, WI 53706, e-mail: ebrahimi@wisc.edu
² Assistant Professor, Engineering Professional Development, University of Wisconsin-Madison, Madison, WI 53706, e-mail: jmtinjum@wisc.edu
³ Professor, Geological Engineering and Civil & Environmental Engineering, University of Wisconsin-Madison, Madison, WI 53706, e-mail: tbedil@wisc.edu

ABSTRACT

Today’s railway freight infrastructure needs to sustain heavier loads and perform satisfactorily between maintenance cycles to be economically and technically sustainable. The frequency of railway maintenance is integral to the quality of railway ballast, which changes continually due to particle breakage and generation of fine particles (i.e., ‘fouling’). In this study, the plastic deformation of ballast under cyclic loading for different fouling materials, such as mineral fouling from crushed ballast and coal fouling from surface spillage, was studied using a large-scale triaxial apparatus. Increasing fouling content (percentage of particles < 4.75 mm) resulted in increased plastic deformation of ballast. A content of mineral fouling greater than 5% significantly changed the deformational characteristics of the ballast in high moisture condition (water content > 10%). The water content of fouling materials (increasing from 5 to 25%) had a significant effect on accelerating the plastic deformation and changing the shape of deformational behavior of ballast from a small rate of plastic deformation (i.e., ‘plastic creep’) to a high rate of plastic deformation (i.e., ‘incremental collapse’). Life expectancy of ballast in various fouling conditions was derived. Fouling can reduce the life expectancy of ballast to less than 2 months under extreme conditions of coal dust fouling (10%) and wet environment conditions (25% water content).
INTRODUCTION

After 60 years of research, the United States (US) has developed the world’s most advanced highway and aviation systems. These systems now face escalating congestion and rising environmental costs. The current US transportation system consumes 70% of the nation’s oil demand and contributes 28% of the nation greenhouse gas emissions (1). In parallel, there has been an increase in volume of rail traffic including additional freight and passenger volume and heavier freight loads carried over the railroad network (2,3). This increased rail capacity has required substantial reconstruction and maintenance of existing rail corridors into a comprehensive heavy freight and, in places, shared high-speed-intercity passenger rail network. The increased volume of rail traffic and freight tonnage is stressing rail substructure, including ballast, subballast, and subgrade (Fig. 1), to levels not experienced to date.

Ballast has a significant role in dissipating and effectively distributing the load from the track surface to the underlying bearing subsurface. Unlike granular layers in pavement structures, railway ballast begins to break and deteriorate under heavy freight loads and the passing of high speed trains, deviating from original specifications and transforming into “fouled ballast.” Ballast fouling starts by internal degradation due to fracture and abrasion between the ballast particles (i.e., ‘mineral fouling’), infiltration from underlying layers (i.e., ‘subgrade fouling’), and surface spillage (e.g., coal fouling’) (3,4,5,6,7,8,9). The main sources of ballast fouling in the US and England are presented in Table 1. The amount of ballast deterioration increases with traffic load repetition and load intensity from the freight cars. Fouling impacts track performance mainly by changing the substructure properties, including (1) loss of effective drainage, (2) formation of “mud-holes”, (3) deterioration of track resiliency, (4) lack of resilience to lateral and longitudinal forces, (5) poor durability after maintenance, and (6) increased rate of deterioration (4,7,9,10). Failure may reoccur in a track shortly after maintenance if initial problems, such as fouling and limited drainage, are not identified and resolved properly. Jefferies and Johnson (11) showed that fouling accumulation is located in the area loaded by
traffic, where tamping tines operate, and at the bottom of the effective ballast layer. Cribs and shoulders show less contamination by fines. Approximately 50% of sites investigated by Jefferies and Johnson (11) showed that crib ballast is acceptable for continued service without cleaning. Lee (3) showed the major fouling is created beneath and at the edge of ties due to stress concentrations. The fouling accumulates in voids from the bottom of ballast layer upwards due to particle breakage and fines penetration from the subgrade. Fouling location from different sources, such as particle breakage, subgrade infiltration, and surface spillage, is summarized in Fig. 1.

A major concern facing the freight rail transportation industry in the US is increasing maintenance costs due to heavier freight loads and substandard track substructure (3). Surfacing and maintenance expenses of the ballast layer (i.e., the large-size aggregate material of railroad substructure) over the past few years has substantially increased; e.g., Burlington Northern Santa Fe (BNSF) Railway has spent approximately $200 million US annually, about 17% of their capital budget (3). The objective of this paper is to correlate fouling levels to the long-term deformational characteristics of ballast. Two sources of fouling material are examined, that from internal ballast particle crushing due to loading (mineral fouling) and that from surface spillage of coal dust. The critical combinations of fouling and moisture that may cause significant deterioration of railway track performance are determined by evaluation of plastic deformations using a large-scale cyclic triaxial testing (LSCT). The stress combinations to be used in the LSCT test were determined by matching the plastic deformations with those obtained from a full-size prototype track model experiment (FSTM). The life expectancy of ballast in various fouling conditions is determined by using the LSCT laboratory data.

MATERIALS

Granitic ballast and subballast, as natural aggregates, were provided from a quarry in Wyoming by BNSF. The particle size distribution of the ballast and subballast (in accordance with ASTM
D6913), in comparison to ballast specification #24 by AREMA (12), are shown in Fig. 2. The particle size distribution of the as-received BNSF ballast is slightly coarser than that of the AREMA specification. The ballast has a maximum particle size of 60 mm and a minimum particle size of 25 mm, while subballast has a maximum particle size of 25 mm. Most of the particles of ballast and subballast have irregular shapes with particle aspect ratio (ratio of the largest and the smallest dimensions of a particle) between 1.5 and 3.5. Based upon visual inspection of thin sections and accompanying X-ray diffraction (XRD), the ballast is 35% granitic and 45% rhyolitic. Highly fouled ballast was obtained from a stockpile in a track yard of the Wisconsin and Southern Railroad Company in Madison, WI. The fouled ballast was sieved and separated into different particle sizes. Particles with grain size < 4.75 mm were designated as fouling materials per the definition of Selig and Waters (4). The fouling material from the fouled ballast (called ‘mineral fouling’) were 70% dolomitic (attributed to particle crushing) and 30% quartzite (attributed to subgrade intrusion), based on XRD analysis. The mineral fouling had low plasticity with liquid limit (ASTM D4318) of 20. The coal source was from the University of Wisconsin-Madison Charter Street Power Plant (a Wyoming-based coal) and was ground to produce the particle size distribution similar to the one observed in the field (8). Coal fouling was also a low plasticity material with liquid limit of 36.

METHODS

Full-Size Prototype Track Model (FSTM) Experiment

A full-size prototype track model experiment (FSTM) was developed to evaluate the scale dependency of long-term deformational behavior of rail ballast under cyclic load. In the FSTM testing, scale effects and the contribution of underlying layers on the deformational performance of the ballast were studied. The result of FSTM testing was used to verify the plastic deformation of the ballast and subballast predicted on the basis of the large-scale cyclic triaxial (LSCT) testing. The prototype FSTM (box size of 24 x 70 in [0.6 x 1.8 m]) experiment is
shown in Fig. 3. A typical tie distance in rail track is approximately 24 in (0.6 m) and only half of the track between two ties was simulated due to symmetry. The FSTM consisted of different layers of track substructure including ballast, subballast, and subgrade. The ballast was compacted at to a maximum dry unit weight ($\gamma_d = 97 \text{ lb/ft}^3, 15.3 \text{ kN/m}^3$) by controlling the volume and weight of the material. A ‘shoulder’ of 1 ft (0.3-m) width was also created. The subballast was compacted by a plate compactor to 100% maximum dry unit weight (standard Proctor, ASTM D 698) at the optimum water content (Table 2), which was confirmed by nuclear density gauge testing. A soft subgrade was simulated by a block of styrofoam with a modulus of elasticity (E) of 14500 psi (100 MPa). Vertical stress (transferred load from a locomotive to the tie) was applied through a servo-hydraulic system (MTS, loading capacity of 20 kips [100 kN]). The deformation during loading repetitions was measured through instrumentation in each layer with linear variable differential transducers (LVDTs). A wooden tie with cross section of 7 x 6 x 21 in (0.18 x 0.15 x 0.53 m) was used, which is in the range of typical tie size for railway track (4,13). The length of the wooden tie was chosen to mimic the length of the rail bearing area (RBA) of a tie, which is between 20 and 24 in (0.5 and 0.6 m) (13).

Large-Scale Cyclic Triaxial (LSCT) Equipment

A prototype LSCT testing apparatus was developed to test a specimen with 12-in (305-mm) diameter and 24-in (610-mm) length. The LSCT was designed, manufactured, and constructed to perform cyclic testing at different confining pressures, frequencies, pulse shapes, and drainage conditions. Air pressure was used to apply confining pressure between 5 and 29 psi (35 and 200 kPa). Both the top and bottom plate caps were machined from 1-in (25.4-mm)-thick aluminum with a snake-drainage pattern to facilitate the drainage of the specimen. A picture of the LSCT test equipment is shown in Fig. 4. Although a loading frequency of 10 to 50 Hz is typical for locomotive speed of 70 MPH (110 km/hr) (14), LSCT tests were performed at 5 Hz due to limitations in the loading device. The plastic deformation of ballast specimens was
determined after 200,000 cycles of loading repetitions. The complete loading system and instrumentation is described by Ebrahimi (14).

**Specimen Preparation For LSCT Test**

A specimen with 12-in (305-mm) diameter and 24-in (610-mm) height (volume of 1.4 ft$^3$ [0.044 m$^3$]) was used in the LSCT test having a height-to-diameter ratio of 2. Bishop and Green (15) recommended a height to diameter ratio of 2 to eliminate the effect of friction at both ends of the sample. The ratio of the specimen diameter ($D$) to maximum particle size ($d_{max}$) was 5. A ratio of 5 to 7 is considered adequate to have a representative volume of specimen within the cell (16,17,18,19). Ballast was compacted to the maximum dry unit weight, with an acceptable variation of ± 5%. The following compaction method provided reproducible compaction data (14) and effectively rearranged and confined particles into a dense state similar to the field, $\gamma_{d \text{ field}} = 97 \pm 5 \text{ lb/ft}^3 (15.3 \pm 0.1 \text{ kN/m}^3) (8,17)$:

1. Place a 4-in (100-mm)-thick lift of ballast in a mold of 12-in (300-mm) diameter.
2. Rearrange particles with a 20-Hz vibratory rod until no more rearrangement is observed (~2 min).
3. Drop a 10-lbs (45-N), 4-in (100-mm) plate from 4-in (100-mm) height 40 times for each lift. The corresponding weight and height limits particle breakage during compaction.

Clean ballast was compacted dry by a vibratory hammer and rodding to reach the density of 97 lb/ft$^3$ (15.3 kN/m$^3$) with specimen weight of 152 lbs (675 N). Four overlapped membrane layers with 0.03-in (0.76-mm) thickness were used to prevent puncture in the membranes during compaction and testing. An air-tight membrane with 0.03-in (0.76-mm) thickness covered the entire specimen, leading to total membrane thickness of 0.12 in (3.0 mm). A membrane correction was applied to the results as described by Kuerbis and Vaid (19,14).

When preparing specimens of fouled ballast, the method of introducing fines and moisture to the specimen is critical (14). One method of preparing fouled ballast specimen is to
mix ballast with moist, fouled material prior to compaction. This mixing method more readily simulates the internal degradation of ballast particles under cyclic loading and infiltration of subgrade into the ballast in which the initial structure of ballast is deformed and the ballast particles are coated by fouling materials. However, a true methodology to simulate in situ fouling via specimen preparation has not been identified due to the continual change of ballast properties. Huang et al. (8) simulated ballast fouling from the surface (e.g., coal dust spillage) by adding coal fouling to the pre-compacted ballast assemblage. Therefore, another potential preparation method is to add wet fouling material to the compacted ballast structure to simulate fouling due to surface spillage or wind-blown fines. The plastic deformation of ballast under cyclic testing prepared with 20% fouled material and different specimen preparation methods was investigated by Ebrahimi (14). The specimens prepared by adding the fouling material to the compacted ballast lifts (i.e., adding fouling to the ballast matrix that has been formed) resulted in plastic deformations less than those of the specimens prepared by mixing the fouling material prior to compaction. In this study, the mineral fouling was mixed with the ballast before molding, whereas the coal fouling was added to the already compacted ballast layer to simulate the introduction of an external fouling source to the ballast and mimic the track fouling process.

RESULTS AND DISCUSSIONS
Verification of LSCT Test Results with FSTM Data
The full-size prototype track model (FSTM) experiment was performed to simulate the track bed in heavy haul freight railroads. The typical axle load of 30 tons (27 tonnes with wheel load = 13.5 tonnes) exerts 7.4 tons (6.8 tonnes) of load on each tie (3.7 tons [3.4 tonnes] for each rail bearing area under a rail), considering 25% of the wheel load is typically transferred to the tie (4, 20). The tie cross section of 7 x 6 in (0.18 x 0.15 m), corresponding to 43 psi (300 kPa) cyclic stress on ballast, was used to account for the effect of the tie size on the deformational performance of the ballast, as shown in Fig. 5. The comparison between the FSTM
experiments and LSCT test results for subballast is shown in Fig. 5a. Subballast in both LSCT and FSTM testing had similar behavior of increasing rate of deformation up to 200,000 loading repetitions (6 million gross tons, MGT). Subballast was tested in confining stress ($\sigma_c$) of 8 psi (55 kPa) and cyclic stress ($\sigma_d$) of 13 psi (90 kPa) in LSCT test. The stress combinations used in the LSTC tests for the subballast and ballast were determined after performing a finite element analysis of a typical track-ballast system and correspond to typical stress combinations in these layers in the field (14). This combination of stresses resulted in a LSCT deformation curve similar to that of the FSTM (Fig. 5a). The results of the FSTM test are compared to that of the LSCT for the ballast in Fig. 5b. Deformation of the ballast under 43 psi (300 kPa) cyclic loading in the FSTM was similar to the deformation of the ballast in the LSCT test with a confining pressure and cyclic stress combination of 13 and 43 psi (90 and 300 kPa), respectively. After determining the representative LSCT test stress conditions through comparison with the FSTM data, the plastic deformation characteristics of ballast in different fouling conditions were determined at $\sigma_c = 13$ psi (90 kPa) and $\sigma_d = 43$ psi (300 kPa) in LSCT test.

**Fouling Effect from the LSCT Tests**

*Critical Fouling and Water Content*

Clean ballast samples from BNSF were tested with different added fouling content and moisture content in the LSCT test. The plastic strains measured as a function of loading cycles are shown in Fig. 6. The data suggest that mineral fouling content up to 20% by itself does not affect the plastic deformations when the material is nearly dry. The rate of plastic deformation of the ballast at low water content, $w = 0$ and 5 %, increases in the initial stage of loading cycles in semi-log-scale graphs, and subsequently, the rate of deformation becomes constant, which signifies ‘plastic creep’. Ballast with high fouling content ($F = 10$ and 20%) and high water content (~15%) exhibits significant increases in the plastic deformation. The rate of plastic
deformation at F = 10 and 20% increases continually with increasing cycles of loading, thus signifying ‘incremental collapse’. Increasing fouling content of ballast over time, due to particle breakage or other sources, gradually alters the behavior of railway track from plastic creep to incremental collapse. Properly timed maintenance cycle should interrupt this deterioration cycle.

Increase of water content in the fouled ballast accelerated the plastic deformation and, more severely, the rate of plastic deformation (dεp /d(lnN)). Based on visual observations, dry fouling did not coat the particles during the process of specimen preparation, while highly moist fouling created a coating around the ballast particles, which likely affected the behavior of particle contact area. Predicting the plastic deformation of ballast in low water content (F = 20% and w = 5%) underestimates the increasing rate of plastic deformation at the field conditions. Water content of fouled ballast inevitably increases in the field after a rainfall. Fouling materials tend to retain the moisture due to the water retention characteristics of the finer fouling particles compared to the clean ballast. Continued studies in this area are necessary to comprehensively evaluate the mechanistic behavior of the water-fines-ballast system.

Different Fouling Materials

Two different fouling materials, mineral fouling and coal fouling, were evaluated. Mineral fouling had a specific gravity (Gs) of 2.6 whereas coal dust had Gs = 1.3. The percentage by weight of mineral fouling produces one half of the volume of coal dust fouling; therefore, 20% by weight of mineral fouling and 10% by weight of coal fouling were tested in the LSCT apparatus, giving the same volume of fouling in ballast. The results of LSCT testing on fouled ballast (mineral fouling and coal fouling) are shown in Fig. 7. For both fouling materials (mineral and coal fouling), an increase in water content from 5 to 15% increased the magnitude and rate of plastic deformation. Mineral fouling exhibited similar sensitivity to water content; the plastic strain of ballast fouled with mineral and coal fouling (F = 20% and w ~ 15%) is εp = 2.6% after 200,000
loading cycles. The rate of plastic deformation of ballast fouled with mineral fouling \( \frac{d\varepsilon_p}{d(\ln N)} = 0.43 \) while that of coal fouling \( \frac{d\varepsilon_p}{d(\ln N)} = 0.52 \) at the same water content \( w \sim 15\% \) and volume of fouling. Note that the mass of mineral fouling is twice the mass of coal fouling at the same volume of fouling.

Life Expectancy of Ballast in Different Fouling Conditions

Plastic deformation of a ballast layer under 360 MGT of traffic loading (60 MGT/yr for 6 years) was predicted using the result of LSCT testing, as shown in Table 3. The fouling and moisture content were assumed constant for predicting the plastic deformation in track service life, even though fouling and water content can vary in the ballast due to the track operation and environmental conditions. The rate of plastic deformation was assumed constant after 25,000 cycles of loading, as shown in Fig. 7 and Table 3. The plastic strain of fouled ballast with coal dust \( (F = 10\%, w = 15\%) \) after 360 MGT is 3.44\%, while that of mineral ballast fouling \( (F = 20\%, w = 13\%) \) is 2.81\%. These strains can be compared to the maximum recommended strain of 3.1\%, which correspond to a plastic deformation of a rail track equal to 1 in (25 mm) designated by FRA (21). The critical FRA safety limit of surface deformation is based upon Class 4 track operation at a speed of 60 MPH (100 km/hr). By limiting the maximum deformation of the ballast to that proposed by the FRA safety limit, the life expectancy of the track in various fouling conditions was calculated in Table 3. Since the FRA safety limit includes deformation of the entire track, the contribution of ballast to the entire plastic deformation was assumed to be 50\% of the whole track deformation (i.e., 50\% of deformation is generated through the superstructure, subballast, and subgrade (13). As presented in Table 3 and Fig. 8, ballast fouled with 10\% coal dust and 20\% mineral fouling \( (w= 15\%) \) reduces the lifetime of the track to 11 MGT (~ 2.5 months for the track with annual operation of 60 MGT/yr) after the fouling content and water content reaches to the levels considered. The lifetime was predicted
assuming the fouling condition and the water content stay constant, which is not necessarily representative of the field environmental conditions.

CONCLUSION

In this paper, the effect of two fouling materials (external coal fouling and internally generated mineral fouling) on the service life of ballast was studied using a large-scale cyclic triaxial (LSCT) test device calibrated with the results of a full-size prototype track model experiment (FSTM). Fouling contents ranging from 0 to 20% with water contents ranging from 0 to 15% were evaluated. LSCT test results show that increased fouling content and water content increases the accumulation of plastic deformation of ballast. There is a critical limit of fouling in constant water content tests, above which the rate of plastic deformation under cyclic loading increases abruptly. Based on service life estimations, ballast fouled with 20% mineral fouling or 10% coal dust (water content = 15%) has a life time of 2.5 months after these conditions develop (for track operating with 60 MGT/yr). The continual change of ballast quality (i.e., increase in the fouling content with service life and moisture due to the environmental conditions) requires a comprehensive model for accurate estimation of ballast life-time. In addition, detection of the level of fouling and water content in the field and use of the laboratory results on the long-term deformational performance of ballast may be integrated to predict the track life and implement a properly timed maintenance. More investigation is necessary to determine the mechanisms of deformation occurring in fouled ballast and to simulate a comprehensive model accounting for the continual change of ballast quality during the service life of the track.

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REFERENCES


**TABLES:**

TABLE 1 Sources of Fouling in US (Selig et al, 1994) and British Railways (Darell, 2005)

TABLE 2 Index Properties of Ballast, Subballast, Crushed Ballast Fouling, and Coal Dust

TABLE 3 Predicted Plastic Deformation of Ballast in Various Fouling Conditions

**FIGURES:**

FIGURE 1 Location of Different Sources of Fouling in Rail Track

FIGURE 2 Particle Size Distribution of Ballast, Subballast, Coal Fouling, and Crushed Ballast Fouling

FIGURE 3 Full Size Prototype Track Model (FSTM) Experiment

FIGURE 4 Large-Scale Cyclic Triaxial (LSCT) Test Equipment, Loading Machine, and Data Acquisition System

FIGURE 5 Comparison between the Results of FSTM experiment and Large-Scale Cyclic Triaxial Testing (LSCT) on (a) subballast and (b) ballast

FIGURE 6 Effect of Fouling Content and Water Content on the Plastic Deformation of Ballast in Large-Scale Cyclic Triaxial Testing (LSCT)

FIGURE 7 Deformation Behavior of Fouled Ballast for Different Fouling Materials (a) Crushed Ballast Fouling and, (b) Coal Dust fouling, in Large-Scale Cyclic Triaxial Testing (LSCT)

FIGURE 8 Life Expectancy of Ballast in Different Fouling Conditions
TABLE 1 Sources of Fouling in US (4) and British Railways (7)

<table>
<thead>
<tr>
<th>Source of ballast degradation</th>
<th>US</th>
<th>Source of ballast degradation</th>
<th>England</th>
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<td>Delivered with ballast (2%)</td>
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<td>Delivered with ballast</td>
<td>NR</td>
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<tr>
<td>Underlying layers</td>
<td>NR</td>
<td>Underlying layers</td>
<td>16</td>
</tr>
<tr>
<td>Tamping 1 tamp/yr, 15 total</td>
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<td>External input Wagon spillage or airborne dirt</td>
<td>52</td>
<td>External input Wagon spillage or airborne dirt</td>
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TABLE 2 Index Properties of Ballast, Subballast, Crushed Ballast Fouling, and Coal Dust

<table>
<thead>
<tr>
<th>Sample</th>
<th>D$_{50}$ (in)</th>
<th>C$_u$</th>
<th>C$_c$</th>
<th>G$_s$</th>
<th>W$_{opt}$ (%)</th>
<th>$\gamma_d$ max (lb/ft$^3$)</th>
<th>LL (%)</th>
<th>PL (%)</th>
<th>Gravel Content (%)</th>
<th>Sand Content (%)</th>
<th>Fines Content (%)</th>
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<td>2</td>
<td>1.4</td>
<td>0.6</td>
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<td>-</td>
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<td>-</td>
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<td>Subballast</td>
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<td>2.6</td>
<td>7</td>
<td>136</td>
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<td>53</td>
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<tr>
<td>Mineral Ballast Fouling</td>
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<td>4.5</td>
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<td>-</td>
<td>20</td>
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<td>0</td>
<td>76</td>
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<td>5.7</td>
<td>1.3</td>
<td>-</td>
<td>-</td>
<td>36</td>
<td>NP</td>
<td>0</td>
<td>73</td>
<td>27</td>
<td>ML</td>
</tr>
</tbody>
</table>

D$_{50}$ = median particle size, C$_u$ = coefficient of uniformity, C$_c$ = coefficient of curvature, G$_s$ = specific gravity, W$_{opt}$ = optimum water content, $\gamma_d$ max = maximum standard Proctor dry density, LL = liquid limit, PL = plastic limit, NP = Low plasticity.

Note: Particle size analysis conducted following ASTM D 422, Gs by ASTM D 854, $\gamma_d$ max and W$_{opt}$ by ASTM D 698, USCS classification by ASTM D 2487, and Atterberg limits by ASTM D 4318.
<table>
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<tr>
<th>Fouling</th>
<th>Fouling Content, ( F ) (%)</th>
<th>Water Content, ( w ) (%)</th>
<th>Rate of Plastic Deformation ( \frac{d\varepsilon_p}{d\ln N} )</th>
<th>Plastic Strain after 360 MGT (%)</th>
<th>FRA (2007)* Limit (%)</th>
<th>Life Time expectancy (MGT)</th>
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<td>14</td>
<td>0.52</td>
<td>4.9</td>
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<td>Mineral Ballast</td>
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<td>0.43</td>
<td>4.65</td>
<td>3.1</td>
<td>11</td>
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</table>

*Based on the maximum surface deformation of 25 mm (1 in), ballast thickness of 15 in (400 mm), and 50% of total deformation from the ballast layer, with the reminder from the subballast and subgrade.
FIGURE 1 Location of Different Sources of Fouling in Rail Track
FIGURE 2  Particle Size Distribution of Ballast, Subballast, Coal Fouling, and Crushed Ballast Fouling
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FIGURE 5 Comparison between the Results of FSTM Experiment and Large-Scale Cyclic Triaxial Testing (LSCT) on (a) Subballast and (b) Ballast
FIGURE 6 Effect of Fouling Content and Water Content on the Plastic Deformation of Ballast in Large-Scale Cyclic Triaxial Testing (LSCT)
FIGURE 7 Deformation Behavior of Fouled Ballast for Different Fouling Materials (a) Crushed Ballast Fouling and, (b) Coal Dust fouling, in Large-Scale Cyclic Triaxial Testing (LSCT)

Note: Fitted semi-logarithmic function was done to the data after 25,000 cycles of loading repetitions

FIGURE 8 Life Expectancy of Ballast in Different Fouling Conditions

Note: Life time (year) was calculated based on 60 MGT/yr-track operation