Reconstruction of Railroad Beds with Industrial Byproducts an *In Situ* Reclamation Material

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Abstract
Development and rehabilitation of railway freight transportation infrastructure needs to address several issues to be technically and economically sustainable. New railroad beds must sustain higher loads, last longer with less frequent maintenance cycles (economics), and ideally minimize energy consumption and generation of greenhouse gases from materials production and construction. In this study, reconstruction of railroad beds was considered by using *in situ* reclaimed materials, such as recycled ballast, and replacement of subballast materials with recycled pavement materials (RPM), with and without enhancement by industrial byproducts, such as fly ash (FA). RPM had approximately similar deformational characteristic as original granitic subballast, with relatively higher rate of permanent deformation. Mixture of RPM with 10% by weight of FA can considerably reduce the amount of plastic deformation of subballast layer, but fatigue cracking must be studied thoroughly. Use of recycled ballast as a replacement for the original ballast will result in larger plastic deformation and an increase in the amount of particle breakage under cyclic loadings, however, the deformation of recycled ballast under large number of cyclic loading is less than the FRA limit for the maintenance. Use of recycled pavement materials and industrial byproducts as subballast layers will reduce the amount of solid waste disposed in landfills and provide more sustainable construction due to lower transportation and production cost.

Introduction
After 60 years, the United States has developed the world’s most advanced highway and aviation systems (FRA, 2009). These systems now face escalating congestion and rising environmental costs. The current US transportation system consumes 70% of the nation oil demand and contributes 28% of the nation greenhouse gas emissions (FRA, 2009). Consequently, there has been an increase in volume of rail traffic including additional freight and passenger volume and heavier freight loads carried over the railroad requiring the
rebuilding of existing railroads into a comprehensive heavy freight and high-speed-intercity passenger rail network. A major concern facing the freight rail transportation industry in the US is the increasing maintenance costs due to heavy freight loads and substandard track substructure. Surfacing and maintenance expenses of the ballast layer (the large-size aggregate material of railroad substructure) over the past few years has substantially increased, e.g., BNSF railways has spent approximately 200 million US$ annually, about 17% of their capital budget (Lee, 2009). Railway ballast begins to deteriorate under heavy freight loads and the passing of high speed trains, deviating from performance specifications and transforming into “fouled ballast”. Highly fouled ballast is replaced with natural clean ballast to provide adequate structural capacity for the track foundation. Fouled ballast can be recycled by separating the fine (fouling) material and remediating the used materials to produce recycled ballast.

Development and rehabilitation of the railway freight transportation infrastructure, must address several issues to be technically and economically sustainable. New railroad beds must sustain higher loads, last longer with less frequent maintenance cycles (economics), and ideally minimize energy consumption and generation of green house gases from material production and construction. These key points are often referred to as the “Triple Bottom Line”- technically sound, economically feasible, and environmentally sustainable. Rehabilitating existing railroad beds to meet increasing load requirements (tonnage, frequency, and speed) while enhancing sustainability is a challenging prospect. One approach that meets these requirements is the reconstruction of railroad beds by using in situ reclaimed materials, such as ballast as well as use of other sources of solid wastes. These include using recycled highway materials as subballast and enhancing their mechanical properties by incorporating industrial byproducts. Use of industrial byproducts, such as self-cementing fly ash, and recycled materials, such as recycled ballast and asphalt pavement, can enhance sustainability aspects. Use of recycled materials and industrial byproducts will reduce the amount of solid waste disposed in landfills and provide more sustainable construction due to the use of in situ materials and the lower transportation cost. This paper will evaluate such an approach.

For highway materials, the life expectancy of recycled pavement materials may not be sufficient for the highway reconstruction as the conventional-natural aggregates are; therefore, strengthening is required. Fly ash (an industrial byproduct of coal combustion power plant) and cement kiln dust (CKD, an industrial byproduct of cement manufacturing) have been added to the recycled pavement material with outstanding outcomes: use of fly ash and CKD can allow a reduction up to 30% of the equivalent conventional base course thickness. Implementation of
cementitous byproducts in rehabilitation of pavements not only reduces the construction cost, but also provides a longer life time (through reduction of permanent deformations) and reduces material disposal and consumption of the natural aggregate resources (Ebrahimi et al. 2010a).

To apply the highway’s approach to railway substructure, recycled ballast and other recycled highway materials can be reused in reconstruction, while cementitious byproducts, such as fly ash and CKD, can improve the mechanical behavior of the recycled materials. Unitizing cementitious byproducts increases the potential for reuse of recycled materials in railway reconstruction. The mechanical properties of railway materials should be enhanced to avoid energy use in removal of existing materials, production of virgin material, and transportation of raw material. The primary objective is to evaluate the use of solid wastes, such as industrial byproducts and reclaimed railroad bed and highway materials, in the reconstruction of railroads. The methods for strengthening of reclaimed materials are investigated in a systematic manner to sustain heavier loads and increase the lifespan of the rail substructure.

**Materials**

To be able to compare the deformational characteristics of recycled materials with natural aggregates, granitic ballast and subballast was provided from a quarry in Wyoming by Burlington Northern and Santa Fe Railway (BNSF). The particle size distribution of the ballast and subballast (ASTM D6913) along with the ballast specification #24 by AREMA (2002) are shown in Fig. 1. The particle size distribution of the as-received BNSF ballast is slightly coarser than that of 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 an irregular shape with particle size ratio (ratio of largest and smallest dimensions of a particle) between 1.5 and 3.5. Based on visual inspection of thin sections and accompanying X-ray diffraction (XRD), the ballast is 35% granitic and 45% rhyolitic. Highly fouled ballast was sampled from a stockpile in a track yard of the Wisconsin and Southern Railroad Company. The fouled ballast was sieved and separated by particle size. ‘Recycled’ ballast was prepared by separating particles between 19 and 50 mm from the fouled ballast. Typically when ballast is undercut and cleaned, the usual practice on heavy North American freight railways is to discard particles smaller than 19 mm and in some cases 25.4 mm (Ahlf 2007). Recycled ballast contains dolomite-source aggregates based on XRD testing results. The compaction characteristic of subballast materials are shown in Fig. 2.
Methods

LARGE-SCALE TRACK MODEL (LSTM) EXPERIMENT

A large-scale track model experiment (LSTM) was developed for determining the long-term mechanical behavior of rail ballast under cyclic load. In the LSTM testing, the scale effect and the contribution of underlying layers on the performance of the ballast can be determined. This method was considerably beneficial when the effect of subballast stabilization on the mechanical behavior of ballast is examined. Service-life performance and lateral flow of ballast can be evaluated in the LSTM with box size of 0.6 m x 2 m. Typical tie distance in rail track is approximately 0.6 m, which due to the symmetry, only half of the track between two ties needed to be simulated. Two wooden ties with different cross section areas of 0.25 x 0.20 x 0.6 m and 0.18 x 0.15 x 0.53 m are used, which is in the range of typical tie sizes used in the railway track (Selig and Waters 1994; Ahlf 2007). The length of the wooden tie is chosen to mimic the length of the rail bearing area (RBA) of a tie which is between 0.5 and 0.6 m (Ahlf 2007). Two different ties create a different contact stress between the tie and ballast (200 and 300 kPa). The LSTM consisted of different layers of track substructure including ballast, subballast, and subgrade. The ballast was compacted at the maximum dry unit weight and a ‘shoulder’ with 0.3-m width was created. Subballast was compacted by a plate compactor and density and water content of subballast was measured after compaction by a nuclear density gauge. A soft subgrade was simulated by using Styrofoam with modulus of elasticity (E) of 100 MPa (Tanyu et al. 2004). Vertical stress (transferred load from a locomotive to the tie) was applied through a servo-hydraulic system (MTS, loading capacity of 100 kN). The deformation of each layer along loading repetitions was measured through the instrumentation in each layer with Linear Variable Differential Transducers (LVDTs). The prototype LSTME is shown in Fig. 3.

TRIAXIAL TESTING EQUIPMENT

A prototype, large grain-size triaxial testing apparatus was developed with the potential of testing specimens up to a 457-mm diameter. The triaxial test is used to investigate the mechanical behavior of ballast and fouled ballast including shear strength, modulus, breakage characteristics, and permanent deformation. This equipment is modified to perform a monotonic and cyclic testing at different confining pressures, rates of deformation and loading, frequencies, pulse shapes, saturation, and drainage conditions. A traditional triaxial apparatus applies the confining pressure by means of a fluid. Air pressure was used to apply a confining pressure range of 1 to 300 kPa (the typical confining pressure experienced in rail substructure). Both the
top and bottom plate caps were machined from 25.4-mm-thick aluminum with a snake-drainage pattern to facilitate the drainage in the large-size specimen (300-mm diameter). Although a loading frequency of 10 to 50 Hz is the typical frequency for a locomotive speed of 110 km/hr, cyclic triaxial testing was performed at a loading frequency of 5 Hz due to the loading machine limitation. The plastic deformation of ballast was determined after 200,000 cycles of loading repetitions.

LOADING SYSTEM AND INSTRUMENTATION

Confining pressure was applied through a Fairchild pressure regulator (Model 10162, 15 to 1000 kPa). The confining pressure was adjusted by QB1 (Model TFEE100, Q1872), and controlled by a Microswitch pressure transducer (Model 242DC100G 700 ± 1 kPa). The air-pressure booster (Proportion Air, Model PSR-2, 2.1 MPa) was used to decrease the time necessary to reach the target confining pressure. A Swagelok pressure gauge (0 - 1000 kPa, Model PGI-63B-MG1-LAQX) was connected to the top of the chamber to monitor the confining pressure. A triaxial acrylic chamber (Abbott Plastics, 12.7-mm-thick wall, tensile strength of 43 MPa) was constructed to house a confining pressure of up to 310 kPa (with safety factor of 3). A brass ASME pop-safety valve (Model 9889K677) provided mechanical safety inside pressure. The confining pressure remained stable within a variation of ±2 kPa during the test. The triaxial test setup is shown in Fig. 4. Axial load was applied by a MTS loading frame (280-L/m MTS hydraulic actuator, 100-kN). The actuator load cell (MTS, 100 ± 0.1 kN) and inside load cell (DCT, DCL 100 ± 0.05 kN) were used to measure the applied load. A flange-mount linear ball bearing (Model 6483K78) with 38.1-mm inside diameter was employed to seal and reduce the friction resistance of the loading plunger (38.1-mm, super corrosion-resistance, stainless steel, precision round rod). Deflections outside and inside the cell were measured by linear variable differential transducers (LVDTs). Because of the low accuracy of the actuator LVDT (MTS, 165 ± 0.1 mm stroke), an outside-LVDT (Solarton, 35±0.01 mm stroke) and an inside LVDT (Omega, 10±0.005-mm, Model AX/5/S) were employed to eliminate the noise in recorded deformations.

SPECIMEN PREPARATION

A specimen with 304-mm diameter and 608-mm height (volume of 0.044 m³) was used in the triaxial test to provide the specimen diameter (D) to the maximum particle size (d_{max}) ratio of 5. A sample size ratio of 5 to 7 provides enough particles across the diameter to give a sufficiently field-representative sample (Marachi et al. 1972, Indraratna et al. 1998, Skoglund 2002). Fair
(2002) indicated that the typical diameter to maximum particle ratio varies between 4.7 and 10. Bishop and Green (1965) recommended the height to diameter ratio of 2 to eliminate the effect of friction at both ends of the sample. Ballast was compacted at maximum dry unit weight with an acceptable variation of ± 5%. The following compaction method provided reproducible compaction data and effectively rearranged and confined particles into a dense state similar to the field, $\gamma_{d \text{ field}} = 15.3 \pm 0.2 \text{ kN/m}^3$ (Huang et al. 2009; Indraratna et al. 1998),

1. A 100-mm-thick lift of ballast was placed in a mold of 300-mm diameter.
2. A 20Hz frequency vibratory rod was used to rearrange the particles until no more movement is observed (~2 min)
3. A 45-N, 100-mm plate was dropped from 100-mm height 40 times for each lift. The corresponding weight and height is proposed to decrease the particle breakage during compaction.

Clean ballast was compacted dry by a vibratory hammer and rodding to reach the density of 15.3 kN/m$^3$ (specimen weight of 675 N). Three overlapped membrane layers with 0.76-mm thickness were used to prevent puncture in the membranes during compaction and testing. An air-tight membrane with 0.76-mm thickness covered the entire specimen, leading to total membrane thickness of 3.0 mm as described by Ebrahimi et al. (2010b).

**Results and Discussion**

*Original and Recycled Ballast*

The large-scale track model (LSTM) experiment was performed in two different configurations to simulate the track bed in heavy haul freight railroads. The typical axle load of 27 tonne (wheel load = 13.5 tonnes) exerts 6.8 tonnes of load to each tie (3.4 tonnes for each rail bearing area under a rail), considering 25% of wheel load is typically transferred to the tie (Talbot 1985, Selig and Waters 1994). The rail bearing area for a typical 2.6-m cross tie is about 0.5-0.6 m (Ahlf 2007). Tie cross sections of 0.25 x 0.20 m and 0.18 x 0.15 m (corresponding to 200 and 300 kPa cyclic stress on ballast) were used to account for the effect of tie size on the deformational performance of railway ballast, as shown in Fig. 5. The results of the large-scale track model (LSTM) were compared with the ones from the large-scale cyclic triaxial (LSCT) test in Fig. 5. Deformation of ballast under 200 kPa cyclic loading in the LSTM is similar to the deformation witnessed in the triaxial test with confining pressure and cyclic stress of 90 and 200 kPa. The plastic deformation of ballast under 300 kPa cyclic stress in the LSTM experiment is similar to that of the triaxial test with confining pressure and cyclic stress of 35 and 300 kPa. For the purpose of comparison between ballast, the stress combination of $\sigma_c = 90 \text{ kPa}$ and $\sigma_d = 200 \text{ kPa}$
was chosen. Original ballast and subballast are tested up to 200,000 cycles of load repetitions, as shown in Fig. 6. Original ballast has plastic deformation of 0.13%; while recycled ballast has 0.38% plastic deformation after 200,000 loading repetitions (corresponds to 5.4 million gross tons, MGT). The amount of breakage (particles passing 4.75-mm sieve) of recycled ballast (0.7%) is relatively three times as high as the one from original ballast (0.2%) under of $\sigma_c = 90$ kPa and $\sigma_d = 200$ kPa. The Recycled ballast with a particle size smaller than original ballast (typically found in the field by sieving and cleaning process during maintenance) is vulnerable to large plastic deformation and also creates more amount of fouling. To simulate the susceptibility of confinement of ballast (due to not-proper shoulders and weaker subgrade) the confining pressure was reduced to 35 kPa. The plastic deformations of recycled and original ballast increases dramatically, while the amount of particle breakage decreases (i.e., the amount of particle fragments passing 4.75-mm sieve is less than 0.05%). The larger permanent deformation of recycled ballast is most likely due to the rounded particle shape of recycled ballast, which reduces particle interlock (Indraratna et al. 2005). Even though, less particle breakage is expected from recycled ballast due to non-angular particle shape, the amount of particle breakage in recycled ballast increases due to more abrasion between particles and different mineralogy causing it to be more susceptible to deformation characteristics.

**Original and Recycled Subballast**

The main function of subballast layers in the railway substructure is to provide a barrier to prevent infiltration of water from the surface and also impede the migration of fine subgrade into the large voids of ballast (creating fouling). However, subballast has to sustain the repetitive loading exerted on the track while exhibiting limited deformation. In this study, the particle size distribution of conventional subballast and alternative subballast (RPM) was chosen because of their similarities so as to solely determine the long-term deformational characteristics of subballast while resembling similar water movement characteristics. The comparison between the LSTM experiment and LSCT results is shown in Fig. 7. Alternative subballast (recycled pavement materials, RPM) in both LSCT and LSTM is shown to have similar behavior of an increasing rate of deformation after 200,000 loading repetitions (5.4 MGTs). Subballast is tested in $\sigma_c = 55$ kPa and $\sigma_d = 90$ kPa as a typical stress combination for the subballast in LSCT, creating the same deformational curve in LSCT and LSTM (Fig. 7). Conventional subballast, from crushed stones, has higher deformation characteristics in the early number of loading repetitions and the rate of plastic deformation decreases by increasing the number of loading repetitions. On the other hand, alternative subballast materials, RPM, have a lower
permanent deformation at the early stage of loading, but increasing rate of permanent deformation by increasing the number of loading repetitions.

Projected permanent deformation of ballast and subballast layer under 350 MGT of traffic loading (60 MGT for 6 years) is shown in Table 2. Alternative subballast (RPM) mixed with fly ash creates the lowest permanent deformation of track. Using of alternative ballast and subballast generates small deformation (less than limit for the ballast and subballast = 38 mm, FRA). However, higher particle breakage potential of recycled ballast should be taken into account in future studies. Use of recycled pavement materials with or without fly ash provides approximately similar or less permanent deformation in the track, however, the effect of fatigue fracture in the stabilized materials with fly ash should be studied in future studies (Ebrahimi et al. 2010).

**Summary and Conclusion**

Conventional and recycled ballast materials were tested in the large prototype track model and triaxial test. The results showed that the recycled ballast creates larger permanent deformation and broken fragments comparing with original ballast. However, the amount of particle breakage and permanent deformation is less than the limit for the maintenance proposed by FRA. More research is required to investigate the mixture of recycled ballast with original ballast in order to confine the excess permanent deformation and the crushing amount of the ballast.

Conventional and alternative subballast materials were tested to evaluate the long term deformational performance of subballast under cyclic load of the track. The rate of deformation of conventional subballast is constant after 200,000 loading repetitions, while recycled pavement materials, as an alternative subballast, has higher rate of permanent deformation. Use of recycled ballast and alternative subballast by using recycled pavement materials and industrial byproducts does not increase the permanent deformation of the track significantly, whereas reduces the permanent deformation in the case of stabilized RPM with 10% by weight fly ash. This study provided an insight into the use of solid waste in reconstruction of railway tracks, which is currently experiencing high natural aggregate demand for construction.
References


Table 1. Index properties for Class 5 base, RPM, and RSG.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$D_{50}$ (mm)</th>
<th>Cu</th>
<th>$C_c$</th>
<th>$G_s$</th>
<th>$w_{opt}$ (%)</th>
<th>$\gamma_{d \text{ max}}$ (kN/m$^3$)</th>
<th>LL (%)</th>
<th>PL (%)</th>
<th>Gravel Content (%)</th>
<th>Sand Content (%)</th>
<th>Fines Content (%)</th>
<th>USCS Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subballast</td>
<td>5</td>
<td>46</td>
<td>3.8</td>
<td>2.6</td>
<td>6.5</td>
<td>21</td>
<td>NP</td>
<td>NP</td>
<td>53.0</td>
<td>40.0</td>
<td>7.0</td>
<td>GW-GM</td>
</tr>
<tr>
<td>RPM</td>
<td>3.89</td>
<td>89.5</td>
<td>2.5</td>
<td>2.64</td>
<td>7.5</td>
<td>21.2</td>
<td>NP</td>
<td>NP</td>
<td>46.0</td>
<td>43.0</td>
<td>10.6</td>
<td>GW-GM</td>
</tr>
<tr>
<td>RPM+10% FA</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>8.5</td>
<td>20.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

$D_{50} =$ median particle size, Cu = coefficient of uniformity, $C_c =$ coefficient of curvature, $G_s =$ specific gravity, $w_{opt} =$ optimum water content, $\gamma_{d \text{ max}} =$ maximum standard Proctor dry density, LL = liquid limit, PL = plastic limit, NP = nonplastic.

Note: Particle size analysis conducted following ASTM D 422, $G_s$ determined by ASTM D 854, $\gamma_{d \text{ max}}$ and $w_{opt}$ determined by ASTM D 698, USCS classification determined by ASTM D 2487, AASHTO classification determined by ASTM D 3282, asphalt content determined by ASTM D 6307, and Atterberg limits determined by ASTM D 4318.
Table 2. Projected Plastic Deformation of Ballast and Subballast in the Case of Using Conventional and Alternative Materials

<table>
<thead>
<tr>
<th>Materials</th>
<th>Plastic Strain %</th>
<th>Plastic Deformation (mm)</th>
<th>Materials</th>
<th>Ballast</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Recycled Ballast</td>
<td>0.51</td>
<td>1.54</td>
<td>Subballast</td>
<td>Original Ballast</td>
<td>2.29</td>
<td>3.12</td>
</tr>
<tr>
<td>Original Ballast</td>
<td>0.23</td>
<td>0.70</td>
<td>Conv. Subballast</td>
<td>Alter. Subballast</td>
<td>2.70</td>
<td>3.54</td>
</tr>
<tr>
<td>Conv. Subballast</td>
<td>0.52</td>
<td>1.58</td>
<td>Alter. Subballast</td>
<td>Stab. Alt. Subballast</td>
<td>0.70</td>
<td>1.54</td>
</tr>
<tr>
<td>Alter. Subballast</td>
<td>0.66</td>
<td>1.99</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Thickness of Layer = 300 mm

Deformation of Ballast and Subballast (mm)

60 MGT / yr for 6 years
Figure 1  Particle Size Distribution of Ballast, Recycled Ballast, Conventional Subballast, and Alternative Subballast
Figure 2 Compaction Characteristics of Conventional Railway Subballast, Alternative Subballast (RPM), and Alternative Subballast Stabilized with Fly Ash
Figure 3 Prototype Large-Scale Track Model (LSTM) Experiment
Figure 4 Large-Scale Cyclic Triaxial (LSCT) Test Equipment (a) and Loading Machine and Data Acquisition System (b)
Figure 5  Comparison Between the Results of LSTM experiment and Large-Scale Cyclic Triaxial Testing (LSCT)

Bolded Text, Closed Symbol:  LSTM experiment, Regular text, Open Symbols:  LSCT
Figure 6 Deformational Behavior of Recycled and Original Ballast in Large-Scale Cyclic Triaxial Testing

Original Ballast
\( \sigma_c = 100 \text{ kPa}, \sigma_d = 200 \text{ kPa} \)
\( \varepsilon_p = 0.026 \ln(N) - 0.19 \)

Recycled Ballast
\( \sigma_c = 100 \text{ kPa}, \sigma_d = 200 \text{ kPa} \)
\( \varepsilon_p = 0.035 \ln(N) - 0.06 \)
Figure 7 Behavior of Ballast and Subballast in Various Recycled and Original Ballast in Large-Scale Cyclic Triaxial (LSCT) Testing

\[ \varepsilon_{p_{\text{conv.}}} = 0.03 \ln(N) + 0.035 \]

\[ \varepsilon_{p_{\text{alt.}}} = 0.065 \ln(N) - 0.4 \]