Ballast Properties and Degradation Trends Affecting Strength, Deformation and In-Track Performance

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ABSTRACT
In-track performance investigations of ballast materials under 36-ton axle load coal trains have been undertaken by Union Pacific (UP) Railroad in conjunction with the Transportation Technology Center, Inc. (TTCI), sponsored by the Association of American Railroads (AAR) and the University of Illinois at Urbana-Champaign (UIUC). The objectives were to quantify the effects of gradation and material type on ballast performance and monitor track settlement behavior over time. Five ballast types (1 through 5) were placed in steel boxes (1 through 5, respectively) to construct test sections along Track 2 of the South Morrill UP subdivision near Ogallala, Nebraska. The South Morrill subdivision carries approximately 230 million gross tons (MGT) of coal traffic annually, primarily on Track 2. Ballast Boxes 1 through 4 were constructed with “clean ballast” materials as they were sieved prior to installation and all material passing the 3/8-in. sieve was removed. Ballast Boxes 5 through 8 were designated as the control ballast boxes, which had the same ballast as Box 2 but were installed as delivered without initial sieving. In-service performance evaluations consisted of sampling and sieving ballast twice a year to monitor degradation. This paper presents the sieve analysis and permanent deformation test results of dry ballast samples collected after 732 MGT of train traffic had traveled over the ballast box test section. Different ballast types showed different rates of degradation based on the percent passing the 3/8 in. sieve. Repeated load triaxial testing was also conducted by UIUC to determine permanent deformation characteristics of each ballast type. For the same ballast type, higher percentages of degraded material (particles passing 3/8 in. sieve) resulted in higher permanent deformation. Permanent deformation trends, indicative of field settlement potentials of ballast materials under repeated train loading, were influenced by both the rock type, i.e., mineralogy and crushing process, and the amount of degraded material present.

INTRODUCTION
Ballast performance under 36 ton axle load coal traffic has been investigated on Union Pacific (UP) Railroad’s South Morrill subdivision near Ogallala, NE. The South Morrill subdivision carries approximately 230 million gross tons (MGT) of coal traffic annually on Track 2, and is the location of the western Heavy Axle Load (HAL) revenue service test mega-site. The investigation is being performed as part of the Track Substructure and HAL Revenue Service Test Strategic Research Initiatives sponsored by the Association of American Railroads (AAR) and the Federal Railroad Administration (FRA). The project is also part of Union Pacific Railroad’s (UP) internal ballast research initiative.

Degradation monitoring began in November 2010 with the installation of new ballast materials from four separate UP sources, labeled ballast boxes 1-8, installed in test zones established on a 2º curve and a tangent location. Ballast boxes 1-4 were sieved after delivery to the site and prior to being installed to discard material smaller than 3/8 in. Boxes 5-8 had the same ballast type (Basalt) as in Box 2, but were installed in the as-delivered condition of the ballast without additional sieving and therefore included material smaller than 3/8 in. For brevity, Boxes 5-8 will be referred to as Box 5 hereafter.

Table 1 lists the mineralogy of ballast types linked to the hardness, strength and degradation resistance. The ballast types were separated by 14 ft. long and 12 ft. wide steel boxes in both zones, with a ballast depth beneath the ties of 14 in. The boxes in the curve zone had steel bottoms, and the boxes in the tangent zone had fabric bottoms to isolate the ballast from the subgrade.

<table>
<thead>
<tr>
<th>Ballast Box</th>
<th>Rock Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Box 1</td>
<td>Granite</td>
</tr>
<tr>
<td>Box 2</td>
<td>Basalt</td>
</tr>
<tr>
<td>Box 3</td>
<td>Quartzite</td>
</tr>
<tr>
<td>Box 4</td>
<td>Rhyolite</td>
</tr>
</tbody>
</table>

© AREMA 2015
The new ballast was sampled before installation in November 2010 and additional samples were taken in April and November 2011, May and November 2012, and May and November 2013 at estimated traffic levels of 120, 234, 320, 480, 538, and 732 MGTs, respectively. The final 732 MGT samples and their respective test regimes are described in this paper.

LABORATORY BALLAST TESTING

Particle Size Distribution
Field ballast materials were sampled at the end of the testing in November 2013 at an estimated cumulative tonnage of 732 MGT. Shallow samples were collected from the bottom of the tie to a depth of 9 to 12 in. below the bottom of the tie. Deep samples were collected from the bottom of the installed steel boxes, 9 to 14 in. below the bottom of the tie. Sampling was performed using a small backhoe and narrow bucket that fit in the cribs between ties. The top ballast was removed to sample only the ballast beneath the bottom of ties as close to the rail seat as possible. Five gallon buckets were filled with material from both the gage side and the field side of the rail. For all of the shallow samples, enough ballast material was provided to UIUC that only contained ballast sampled from the tangent zones of the track. For the deep ballast tests, there was not enough material provided to make laboratory test specimens using only samples taken from the tangent zones of the track, so ballast sampled from the curved portion of the track had to be mixed with the ballast from the tangent portion of the track. Despite this, the combined material was sieved and the combined gradation was also used for analysis.

After sampling in the field, the degraded ballast at 732 MGT was shipped to UIUC in 5-gallon buckets for testing. The field degraded ballast was oven-dried and sieved according to ASTM C136 (1) standard sieve analysis procedure for coarse aggregates, returned to each 5-gallon bucket, labeled, and stored indoors. The results of the shallow sample sieve tests for each box are shown in Figure 1 and the deep sample sieve tests results are shown in Figure 2. Note that the sieves used did not have large enough openings to reach the 100 percent passing mark so the sieve diameter for 100% passing was used from the ballast at 0 MGT which was 3 in. Selig and Waters (2) established “percent fouling material” as the ratio of the dry weight of material passing 3/8 in. sieve to the dry weight of total sample. Accordingly, the remainder of this paper will use the material passing the 3/8 in. sieve size when referring to the degraded portion of the ballast samples.
Figure 1. Shallow sample gradations from all five ballast boxes after 732 MGT of traffic

Figure 2. Deep sample gradations from all five ballast boxes after 732 MGT of traffic

Permanent Deformation Testing

*University of Illinois Ballast Triaxial Tester (TX-24)*

Permanent deformation tests were conducted on dry ballast samples using a large triaxial test machine called the TX-24, specifically built for railroad ballast testing and characterization. The TX-24 can accommodate a 12 in. diameter by 24 in. tall cylindrical ballast specimen. Testing can be conducted in two different modes: a displacement controlled mode for monotonic strain-controlled shear strength tests or a load controlled mode for cyclic dynamic pulsing (repeated load) tests. The repeated load dynamic pulsing tests were performed on the 732 MGT degraded ballast materials to determine their permanent deformation trends as described in Lekarp et al. (3).
The TX-24 is equipped with a 22-kip capacity MTS servo-hydraulic actuator (model 204.63). The vertical load is recorded using a 20-kip capacity Honeywell load cell (model 3174). The confining pressure is applied using compressed air. The sample is confined inside a 0.75-in. thick acrylic chamber having an inner diameter of 24 in. and a height of 36 in. User-defined load pulses and displacement ramps are generated using LabVIEW™, which are then transmitted to the actuator through an MTS 407 controller. Three linear variable differential transformers (LVDTs) (TransTEK Series 13±1 in. stroke), positioned 120 degrees apart, are mounted on the specimen to reliably measure the vertical displacements. The vertical displacement is the average of the three LVDT readings. In the case of specimen misalignments or ball bearing type large stone movements during testing, the average of the two LVDTs with the closest readings is used. Further details can be found in Mishra et al. (4).

Sample Preparation and Testing

The preparation of the specimen required that the ballast be compacted, confined by a vacuum applied to the inside of the specimen, and then sealed within the testing chamber where confinement is then transferred from the interior vacuum to compressed air that is exterior to the specimen. Each ballast sample was prepared inside an aluminum split-mold. Before compaction, two 0.03-in. thick latex membranes used in the first phase of sample preparation to confine the specimen were secured to the specimen base plate with an O-ring. The split mold was then bolted together around the O-ring to form a 12-in. inner diameter cylinder and the membranes were stretched tight along the sides of the mold. To prevent fines from clogging the confinement vacuum, a geosynthetic fabric was placed at the bottom of the specimen.
To compact, each ballast sample was prepared inside the aluminum split-mold by compacting four 6-in. lifts for 4 seconds with a 100-lb. jack hammer outfitted with a 12-in. diameter plate on the end. The amount of ballast added was carefully selected to ensure a compacted lift height of 6±0.5 in. The compaction procedure did not target a certain density; rather it was a process control. The achieved density was recorded for each test specimen and had no clear trend with the amount of permanent deformation accumulated. The top one inch of each of the first three compacted layers was scarified to ensure interlock at the layer interfaces. An aluminum plate was then inserted on the top of the specimen and ensured to be level using a spirit level. Before removing the split-mold, the tops of the membranes were twisted and sealed with zip ties as a temporary seal for confinement. The vacuum pump was then turned on and a confining pressure of approximately 8 psi, commonly used in ballast permanent deformation tests by researchers, was applied to the specimen. After achieving stable vacuum confinement pressure, the split mold was disassembled and a third airtight (seamless) membrane was added to the outside of the specimen as the first two membranes generally become punctured during compaction. The membranes were finally sealed to the top and bottom plates using steel hose clamps.

Following the compaction process, the axial LVDTs were mounted to the sides of the specimen at 120° as shown in Figure 3(b). The LVDTs measure axial movements and are set at a starting position of 10.5 in. centered on the midpoint of the specimen to eliminate boundary effects at the specimen ends. After testing, each LVDT displacement reading was graphed, evaluated and commonly, averaged with the other two to account for specimen leaning. The LVDTs were held in place using springs as shown in Figure 3 and double sided industrial strength tape was used to ensure sound contact between the LVDTs and the surface of the outer membrane. A load cell was next placed on the top plate for measuring the

Figure 3. UIUC TX-24 triaxial test machine used in ballast testing

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applied load from the hydraulic actuator. An acrylic cylinder was then placed around the specimen to use as a confinement chamber and a stainless steel cover used as a top to seal the chamber. The chamber was finally carefully mounted on the load frame using a forklift. The confining pressure of 8 psi was then transferred from the vacuum pump to the acrylic chamber using an air compressor and a loading rod was installed to transfer load from the hydraulic actuator to the specimen. Once the confining pressure was completely applied by the air within the acrylic chamber, the vacuum pump was detached so that the interior of the specimen remained at atmospheric pressure throughout the test. At this point, pulsed loading was begun by applying a vertical deviator stress of 24 psi for 0.4 seconds with 0.6 seconds for the rest. Previous research has shown that such a load pulse corresponds to a rail car with 40-ft truck centers operating at 40 mph (5). This dynamic pulse loading was repeated 10,000 times for each test.

RESULTS AND DISCUSSION
Results from the sieve analyses (Figure 1 and Figure 2) show that the sample buckets representing the deep portion of each ballast box had more material passing the 3/8 in. sieve than those for the shallow portion of the ballast boxes.

Table 2 shows the percent passing 3/8 in. sieve for both the shallow and deep samples from each ballast box, where on average more of this degraded material is present in the deep samples. The larger portion of degraded material in the deep samples can be explained by the downward migration of the finer materials in the ballast due to gravity and vibrations from passing trains. Although Box 2 Deep started with no material passing the 3/8 in. sieve at installation, interestingly, it became more degraded at 732 MGT than its Box 5 Deep counterpart, which was installed as delivered from the quarry with the passing 3/8 in. sieve fraction. This suggests that the degradation rate of clean ballast without minus 3/8 in. material was higher than that of the as-received ballast and that the fine fraction may have provided a cushioning effect to slow down the degradation of the ballast. In contrast, the results from Box 2 and 5 Shallow are the opposite which could be a result of the sampling procedure which involved using a backhoe to collect ballast. To verify whether the degradation rate conclusion is valid in future projects, a better sampling method is needed.

Table 2. Percent of material passing 3/8 in. sieve for the prepared permanent deformation specimens

<table>
<thead>
<tr>
<th></th>
<th>Percent Passing 3/8 Inch Sieve (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shallow</td>
<td></td>
</tr>
<tr>
<td>Box 1</td>
<td>3.5</td>
</tr>
<tr>
<td>Box 2</td>
<td>8.9</td>
</tr>
<tr>
<td>Box 3</td>
<td>2.9</td>
</tr>
<tr>
<td>Box 4</td>
<td>8.3</td>
</tr>
<tr>
<td>Box 5</td>
<td>14.3</td>
</tr>
<tr>
<td>Deep</td>
<td></td>
</tr>
<tr>
<td>Box 1</td>
<td>13.5</td>
</tr>
<tr>
<td>Box 2</td>
<td>22.2</td>
</tr>
<tr>
<td>Box 3</td>
<td>16.4</td>
</tr>
<tr>
<td>Box 4</td>
<td>17.6</td>
</tr>
<tr>
<td>Box 5</td>
<td>16.1</td>
</tr>
</tbody>
</table>

After conducting three permanent deformation tests for each ballast sample, the data from each test was plotted and the average of the deep and shallow tests was determined. An example of this is provided in Figure 4 where the individual tests from Box 3 Shallow and Deep are shown with smaller symbols and thinner lines, while the averages for the deep and shallow tests are shown with larger symbols and thicker lines. Note that the data points used for each line are enlarged for the reader, when in reality the recorded data points in this figure are much more closely spaced, forming the thin line seen connecting the enlarged data points. Figure 4 shows the shallow tests with consistently lower permanent.
deformation levels at the different load cycles compared to the deep tests. This observation is true not only for Box 3, but for all the ballast boxes. Since the only difference between the deep and shallow samples are the gradations, the reason for this consistent trend is most likely due to more degraded material present within the deep samples.

![Graph](image)

*Figure 4. Ballast Box 3 permanent deformation test results for shallow and deep samples*

Once the average permanent axial strain was determined for each ballast box at both deep and shallow sampling depths, the results were compiled and are shown in Figure 5 for the shallow samples and in Figure 6 for the deep samples. At 10,000 loading cycles, the average permanent strain range for the shallow samples is 0.81% - 0.94% for the corresponding degraded material content range of 2.9% - 14.3%. At 10,000 loading cycles, the average permanent strain range for the deep samples is 1.01% - 1.31% corresponding to a degraded material content range of 13.5% - 22.2%. In general, it is seen that the deeper samples result in higher average permanent axial strains but that the order of the ballast boxes differs from Figure 5 to Figure 6. For example Box 1 had the highest average permanent axial strain of the shallow samples while Box 3 had the highest average permanent axial strain of the deep samples. Part of the reason for this variation is because these tests were performed with two variables: rock type and gradation. To be able to make accurate conclusions, one variable must be held constant while changing the other. Holding the rock type variable constant while changing the gradation can be done for Box 2 and Box 5 since they are both the same rock type (basalt).

The variability between tests is captured in Figure 7, where the average permanent axial strain for each box and depth is plotted with whisker lines showing one standard deviation from the average permanent strain. After examining the standard deviation whiskers, it is evident that the variance of the permanent axial strain always decreases when comparing the shallow tests with the deep tests except for the case of Box 5. This suggests that the more degraded a sample becomes, the more consistent its response will be during a permanent deformation test because the degraded material is mixed more uniformly within the specimen as opposed to only in concentrated locations.
Figure 5. Shallow sample average permanent axial strains accumulated during permanent deformation tests for each ballast box (Box 2 is the blue line with circular symbols while Box 3 is the orange line with triangular symbols).

Figure 6. Deep sample average permanent axial strains accumulated during permanent deformation tests for each ballast box.
CONCLUSIONS
This paper described the effects of gradation and rock type on the degradation behavior of different ballast materials investigated for performance under coal trains with 36-ton axle loads. Five ballast types (1 through 5) were sampled, dried, and sieved to study the degradation behavior after 732 MGT of train traffic. Repeated load triaxial testing was conducted in the laboratory to determine permanent deformation characteristics of each ballast type tested in dry conditions. The following are the main conclusions:

- Based on the percentage of material passing the 3/8 in. sieve (degraded material), different ballast types showed different rates of degradation:
  - Basalt (Box 2) showed the highest rate of degradation for both deep and shallow samples;
  - Rhyolite (Box 4) showed the second highest rate of degradation;
  - Granite and Quartzite (Boxes 1 and 3, respectively) had the lowest degradation rates among the rock types tested.

- For the same ballast type, higher percentages of particles passing the 3/8 in. sieve consistently resulted in higher permanent deformation.

- The granite ballast from Box 1 permanently deformed more than the quartzite, as indicated in Figure 5, based on the observation that the samples tested (Box 1 and Box 3 Shallow) had nearly identical gradation curves (see Figure 1). Comparisons with the other shallow sampled rock types are not possible because the gradations are significantly different among the ballast boxes.

- The rhyolite ballast permanently deformed nearly identical to basalt, as indicated in Figure 6, because the samples tested (Box 4 and Box 5 Deep) had nearly identical gradation curves (see Figure 2) to start with. Comparisons with the other deep sampled rock types are not possible because the gradations are significantly different among the ballast boxes.

- Field settlement potentials of ballast materials under repeated train loading are influenced by several factors including, but not limited to, the rock type (mineral composition) and the amount of degraded material present. To make definitive conclusions about the effect of rock type and mineralogy on the permanent deformation characteristics, it is first necessary that different ballast types be tested at the same gradation to eliminate the
gradation as a variable affecting the permanent deformation potential. Based on the field collected samples, the permanent deformation characteristics are affected by both the rock mineralogy and the gradations.

- Comparing the amounts of degraded material at 732 MGT from the Box 2 and Box 5 Deep and Shallow locations, no clear trend can be established between clean ballast and the rate of ballast degradation. This may be due to the use of a backhoe as the sampling method in this study and the associated sampling errors and inconsistencies that have developed. A more consistent sampling technique is recommended for future work.

**ACKNOWLEDGEMENTS**

The authors would like to thank the research engineers James Meister, Aaron Coenen, and Greg Renshaw, and Mr. Marc Killion at the Advanced Transportation Research and Engineering Laboratory (ATREL) at the University of Illinois at Urbana-Champaign for their help and guidance. Graduate students Hasan Kazmee, Pengcheng Wang, and Ilhan Cetin were also extremely helpful; without their help the many hours of preparation and testing would have been doubled at the least.

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Samuel Douglas
Union Pacific Railroad
Presentation Outline

- Project objectives
- Field test setup
- Ballast types & gradations
- Permanent deformation
- Conclusions

Project Location

Track 2 of South Morrill UP Subdivision; Ogallala, Nebraska

Source: Alan Craig

Project Overview

- Ballast performance under 36-ton axle load coal traffic
- The South Morrill subdivision carries ~230 MGT of coal traffic annually on Track 2
- Track 2 is the location of the western Heavy Axle Load (HAL) revenue service test mega-site
- The investigation is being conducted as part of the Track Substructure and HAL Revenue Service Test Strategic Research Initiative (SRI)
- Sponsored by AAR / TTCI and FRA
- The project is part of UP’s internal ballast research initiative

Track Substructure SRI Objectives

- Investigate effects of ballast material types and degradation trends on strength, permanent deformation and in-track performance

Gradation

Aggregate Type

Performance under HAL

Field Setup

Ballast Box Installation

Ballast Types Installed:

- Box 1: Granite
- Box 2: Basalt
- Box 3: Quartzite
- Box 4: Rhyolite
- Box 5-8: Basalt

- Very little material passing 3/8" (<1.2%)
- Installed as received from the source (1.9% passing 3/8")

Ballast Box Installation

Source: Union Pacific

Project Overview

- Ballast installation: November 2010
- Four separate UP sources
- Labeled ballast boxes 1-8
- Test zones established on
  - 2º curve and
  - Tangent location

Source: Union Pacific

Ballast Box Installation

Supplier #1
Supplier #2
Supplier #4
Supplier #5
Supplier #3
Control (x4)
Supplier #4
Supplier #5
Supplier #3
Supplier #2
Supplier #1

- Very little material passing 3/8" (<1.2%)
Field Setup (cont’d)

Source: Union Pacific

Installed Ballast Gradations

Box 1: Granite  
Box 2: Basalt  
Box 3: Quartzite  
Box 4: Rhyolite  
Box 5: Basalt

Field Sampling

Sample Depths:
- Shallow:
  - Bottom of tie to 9-12 in. below tie
- Deep:
  - 9 in. below bottom of tie to bottom of steel box

Backhoe Sampling

Source: RT&S October 2014 article by Basye, Li, Douglas and Gehriinger

Approximate Traffic Volume Over Time

- Samples taken at approximately:
  - 120 MGT  
  - 234 MGT  
  - 320 MGT  
  - 480 MGT  
  - 538 MGT  
  - 732 MGT
- Focus of this paper:
  - 732 MGT samples

732 MGT Shallow Sample Gradations

Box 1: Granite  
Box 2: Basalt  
Box 3: Quartzite  
Box 4: Rhyolite  
Box 5: Basalt

732 MGT Deep Sample Gradations

Box 1: Granite  
Box 2: Basalt  
Box 3: Quartzite  
Box 4: Rhyolite  
Box 5: Basalt
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Track Substructure SRI Objectives

- Investigate effects of ballast material types and degradation trends on strength, permanent deformation and in-track performance

Field Setup

Ballast Box Installation

- Ballast box installation: November 2010
- Four separate UP sources
- Labeled ballast boxes 1-8
- Test zones established on
  - 2º curve and
  - Tangent location

Ballast Types Installed:

- Box 1: Granite
- Box 2: Basalt
- Box 3: Quartzite
- Box 4: Rhyolite
- Box 5-8: Basalt

Very little material passing 3/8” (<1.2%) Installed as received from the source (1.9% passing 3/8")

Source: Union Pacific
Ballast Degradation Monitoring

Box 1: Granite  Box 2: Basalt
Box 3: Quartzite Box 4: Rhyolite
Box 5: Basalt

- Different rock types showed different rates of degradation
- Fluctuations (e.g., Box 4) attributed to field sampling error

Ballast Triaxial Specimen

- Sample is prepared inside an aluminum split-mold
- Four equal lifts (24 in. final height)
- Compaction: 4 seconds per lift using a vibratory jack hammer
- LVDTs mounted on the specimen at mid-depth

Permanent Deformation (PD) Testing

- TX-24 Loading Frame
  - MTS actuator capable of applying up to 22-kip dynamic loading
  - On-specimen load measurement: 20-kip capacity load cell
  - Three axial LVDTs located at 120° to measure on-specimen axial deformation (range = ± 1 in.)
  - One circumferential LVDT (range = ± 0.5 in.) for measuring change in sample diameter

Permanent Deformation (PD) Testing

- 10,000 load cycles
- Confining pressure: 8 psi
- Max deviator stress: 24 psi
- Haversine load pulse
  - Loading period: 400 ms
  - Rest Period: 600 ms
- Replicating 40 mph train

Source: Mishra et al. 2012
**TX-24 Test Run**

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**Box 1 Shallow PD over Time**

- PD tests were conducted on shallow depth samples at all collected MGT levels.
- PD generally increases with MGT.

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**All Boxes PD with Time**

- PD generally increases with MGT for all rock types.
- Fluctuations are believed to be due to sampling method inconsistencies.

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**Box 3 Permanent Deformation (732 MGT)**

- Three (3) tests performed per sample depth.
- Results were averaged.
- Deep samples PD consistently higher than shallow samples.

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**732 MGT Shallow Sample PD Results**

- PD box order does not correspond to minus 3/8” box order.
- Differences between boxes are small (range: 0.80%–0.95%).
- Comparison is difficult due to 2 variables present: gradation and rock type.
732 MGT Deep Sample PD Results

- More minus 3/8” material present than in shallow samples
- PD differences are still small, but range is higher (1.0%-1.3%)
- Comparison is difficult due to 2 variables present: gradation and rock type

![Deep 3/8 Inch Sieve Results](image)

Organic Carbon Percentages

- CHN Testing of the minus No. 200 sieve fraction
  - Samples pretreated with HCL to Remove inorganic carbon
- Pure coal dust has 55-58% organic carbon
- It took at least 732 MGT to accumulate significant amounts of coal fines
  - Negative effects on PD

![Organic Carbon Percentages Chart](image)

Conclusions

- Box 1 (Granite) & Box 2 (Basalt) – coarser initial gradations
- Degradation rates (Highest to Lowest):
  1. Basalt (Box 2)
  2. Rhyolite (Box 4)
  3. Granite and Quartzite
- For the same ballast type, more degraded material (measured as the percentage passing the 3/8 in. sieve) consistently produces more permanent deformation

![Conclusions Chart](image)

Current and Future Work

- High resolution image scanning for particle shape and angularity information
- Permeability testing for the effects of ballast degradation on permeability
- Wet PD testing
- Wet and dry shear strength testing

![Current and Future Work](image)
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- Eric Gehringer, UP
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