Using Petrography to Evaluate Railroad Ballast Suitability: A Case Study

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ABSTRACT
Railroad ballast is uniformly-graded coarse aggregate placed between and immediately underneath the crossties. The purpose of ballast is to provide drainage and structural support for the heavy loading applied by trains. Railroad ballast represents a large expense for Class I freight railroads, and there is increased emphasis on better evaluation of virgin ballast aggregates to determine quality. However, physical testing can be expensive and time consuming. Petrographic examination of ballast aggregates offers a method to quickly examine ballast aggregates for their suitability in Class I freight railroad mainlines. Petrography is the branch of petrology (the study of rocks) that focuses on the detailed description of rocks. This paper features a case study of two rhyolite aggregates that were in use for a
Class I freight railroad. First, physical properties of the ballast aggregates are examined, followed by an examination of the results of physical and mechanical testing. Finally, a petrographic examination is conducted on the two ballast aggregates using hand samples and microscope thin section. On the basis of the grain size of the groundmass of the two rocks and their single particle crush test results, a major cause of the poor performance of one of the aggregates was determined to be petrographic in nature. Its large grain size was identified as a feature that may have negatively impacted its performance. This aggregate also had the most flat and elongated shape to make it susceptible to breakage under traffic loading. Using the knowledge and methodology gained from this preliminary work, further petrographic examination into aggregate performance may hold promise for quicker and cheaper evaluation of ballast aggregates.

INTRODUCTION
Railroad ballast is uniformly-graded coarse aggregate placed between and immediately underneath the crossties. The purpose of ballast is to provide drainage and structural support for the heavy loading applied by trains. Railroad ballast represents a large expense for Class I freight railroads, and there is increased emphasis on better evaluation of virgin ballast aggregates to assess how variations in the source properties of new ballast aggregate materials provided by suppliers may influence ballast performance and quality.

Many materials may be used as ballast. Among them crushed stone, crushed slag, prepared and pit-run gravel, chat, cinders, chert, burn clay, sand, seashells, and even dirt have been used as ballast materials. With today’s heavy axle loads and the use of concrete ties, crushed stone is used nearly exclusively on most mainlines. Furthermore, Class I railroads nearly exclusively use crushed stone derived from igneous rocks or some of the more durable metamorphic rocks for their tracks. AREMA broadly defines three categories of premium stone: granitic, trap rock, and quartzite. Since physical testing can often be expensive and time consuming to evaluate different sources of ballast, petrographic examination of ballast aggregates offers a method to quickly examine ballast aggregates for their suitability in Class I freight railroad mainlines.

Mineralogy is the study of minerals. Rocks are composed of assemblages of minerals, and commonly classified according to their mineral composition. A mineral is defined as a naturally-occurring crystalline solid with a definite chemical composition and atomic structure. The mineral content and texture of a rock essentially define a particular rock, and define how it will behave. On the other hand, petrology is a branch of geology, and petrography is the branch of petrology that focuses on detailed descriptions of rocks. A petrographic description of a rock will include items such as mineral content, texture, and any other relevant information about the rock. This will involve inspection of hand samples of a rock as well as analysis of a thin section through a petrographic microscope. A thin section is a representative section of a rock that is cut, mounted to a glass slide and ground to a thickness of 30 μm. This allows for mineral identification through visual color analysis and identification of micro-textures of the rock. In addition, X-ray diffraction can also be used to help identify the minerals making up a particular rock.

The petrography of railroad ballast will influence how it breaks at the quarry, and how it behaves or degrades in track. In the past, researchers and organizations have had success using petrography as a factor in evaluating aggregates. The Department of Highways (DOH) of Ontario found petrography to be one of the most important factors in evaluating and determining aggregate performance in roads (1). First, aggregate composition was determined to find the percentage of rock types within each aggregate. Then, based on performance, each rock type was given a rank of 1 (excellent) to 6 (poor). This rank was then multiplied by the percentage of each rock type in the aggregate to give a weighted average. After several years testing this method, the DOH of Ontario concluded that their method was among the most significant of all quality tests, the quickest test, more reliable and better indicative of performance than absorption or abrasion alone, and adaptable to both field and laboratory. In addition, Selig and Waters (1) identified many petrographic qualities of aggregates that would likely lead to poor performance in ballast.

This paper presents a case study of two rhyolite aggregates with different characteristics analyzed to determine petrographic properties that may have affected these aggregate characteristics. Though there
is uncertainty over the exact crushing methods used, petrography will likely affect how these aggregates crushed and thus influence their shape properties. First, gradation, specific gravity, absorption, density, and void ratio properties were determined. Next, the image analysis-based particle shape properties and a series of mechanical behavior tests were performed.

**BACKGROUND AND COMPARISON OF AGGREGATES STUDIED**

Rhyolite is one of the more common igneous extrusive, or “trap rock,” aggregates found in nature. It is mineralogical composition is equivalent to the pure granite rocks. This section contains a description and comparison of the physical properties of two rhyolite aggregates of different characteristics, i.e., Ballast A and Ballast B, as well as comparisons of the physical test results of the two ballast aggregates. Ballast A, shown in Figure 1, is a very dark aggregate (melanochratic), mostly a dark purple to brown with reddish tones and spotted with white to light pink crystals (known as phenocrysts). On the contrary, Ballast B, shown in Figure 2, is a very light in color (leucocratic) and white to gray to very light pink and is spotted with black phenocrysts.

![Figure 1 – Photograph of Ballast “A” rhyolite trap rock aggregate](image-url)
Physical Properties
Ballasts A and B have very different physical properties. Figure 3 presents the gradation curves or particle size distributions of Ballasts A and B. Figure 3 also compares Ballasts A and B to the Union Pacific Railroad (UP) and BNSF Railway’s Joint Engineering Specification’s Class I ballast gradation (4) and AREMA’s No. 24 recommended specification, both of which are intended for use on mainline tracks. Both ballasts failed to meet both specifications. Table 1 lists the coefficients of curvature and uniformity, specific gravity, and absorption properties for Ballasts A and B. Although both ballast materials have similar coefficients of uniformity and curvature, Figure 3 indicates that Ballast B contains more fine particles than Ballast A. Although Ballasts A and B had similar specific gravities, Ballast B had significantly higher absorption than Ballast B (see Table 1).
Table 1 also lists the aggregate shape or morphological properties quantified using imaging-based shape indices measured using the University of Illinois Aggregate Image Analyzer (UIAIA) (2,3). Flat and Elongated ratio (FER) is the ratio of an aggregate particle’s maximum to minimum dimensions. Angularity is the count of sharp corners and fractured or crushed sides, and surface texture has to do with rough or smooth surfaces. Standard methods to capture these properties such as ASTM D4791 for FER, and ASTM D5821 for angularity are not only time consuming but subjective. To overcome these issues, the University of Illinois developed an Aggregate Image Analyzer, i.e., UIAIA, to quantify FER, Angularity Index (AI), and Surface Texture Index (STI). AI is an imaging-derived particle shape property that measures the angularity of aggregate particles, wherein a lower value indicates a more cubical or spherical aggregate and a higher value indicates a less uniform, angular rock (2). FER is simply the ratio of the longest dimension of a particle to the shortest dimension. Finally, STI is a measure of the micro-irregularity of a rock, wherein a higher value indicates a rock with a rougher surface (3). Ballasts A and B have nearly identical average AIs although Ballast B has a higher surface texture, i.e. rougher surface texture than that of Ballast A. The most interesting shape property of Ballast B is that it has a significantly higher FER than Ballast A which should make Ballast B’s particles more susceptible to breakage.
Physical and Mechanical Tests

Procedures

Three physical tests relevant to this paper were conducted on the two ballast aggregates. Direct shear testing was done according to the procedures laid out by Wnek et al. (5). Single particle crush testing was carried out according to the procedures by Lim (6) and modified to work with equipment readily available. Finally, a Los Angeles Abrasion test was carried out according to the procedure in ASTM C535, except that the ballast aggregate was also tested to 400 turns to study early degradation of the aggregates.

According to Lim (2004), “the single particle crush test is an indirect tensile test to measure the strength of ballast particles by compressing individual particles between two flat platens to induce tensile stress within the ballast particle,” (6). When an aggregate particle is compressed during the Single Particle Crush Test (SPCT), it will normally fail through fracture. Once a critical value of stress is reached, the aggregate particle will break into several pieces. The SPCT makes several assumptions during testing and for interpreting the results. It assumes that the aggregate particles are quasi-spherical and that the stress field within the particles is homogenous and isotropic. Quasi-spherical particles help reduce the contact area on the top and bottom platens. This increases the likelihood of bulk fracture (desirable) over surface fracture. While this is a difficult goal to achieve, avoiding bending failure during testing is essential for the test results of the SPCT to be valid. This can be done by avoiding particles with two or more contact areas, such as that indicated in Figure 4.

![Diagram of Single Particle Crush Test](https://via.placeholder.com/150)

**Figure 4 – Example of particle experiencing failure in bending during a single particle crush test**

The failure force on the particle must be converted into a tensile stress to normalize the strengths for particle size. This was done by estimating the area of the particle at failure, $d_f$, using dimensions obtained from the UIAIA. The particle size at failure, $d_f$, was then squared to estimate the area. Thus, tensile stress at failure is computed by dividing the failure force by the square ($d_f^2$) of the largest broken particle size at failure. Fifteen particles from the three dominant sieve sizes of both ballasts were tested, and processed to create Weibull survivability plots.

Results

Ballast A had significantly higher shear strength than Ballast B as obtained from testing each ballast assembly in shear box type direct shear tests (see Figure 5). High values of absorption affected shear
strength properties detrimentally. On the other hand, Ballast A had higher statistical particle strength than Ballast B from SPCT experiments, as shown in Figure 6. Particle strength was found to increase with decreasing particle size. Finally, Ballast A and B had similar durability and degradation trends at both 400 and 1,000 turns of the LA Abrasion drum as highlighted in Figure 7. From Figure 7, degradation trends and aggregate durability do not seem to be affected by the petrographic differences between the two rocks.

Figure 5 – Interpolated shear strength properties of Ballast A and Ballast B obtained from direct shear testing (1 psi=6.89 kPa)

Figure 6 – Single particle crush test results of Ballast A and Ballast B. Each data point represents a particle size group (1 psi=6.89 kPa, 1 in=2.54 cm)
PETROGRAPHIC EXAMINATION PROCEDURES

First, each aggregate was examined in hand sample for relevant characteristics. The rock was examined using a 10x magnification hand lens and pictures were taken of the main modes of each ballast aggregate particle to help determine the percentage of phenocrysts within the porphyritic rock (see Table 2 for relevant terms). Next, a representative rock was cut to a rectangular piece and made into a 30 μm thin section. The samples were vacuum impregnated with blue epoxy to help identify voids in the rock and stains were added to help distinguish between alkali (yellow-brown stain) and plagioclase (red stain) feldspars. Then, the thin sections were examined under petrographic microscope in Plane Polarized Light (PPL) and Cross Polarized Light (XPL). Then, photomicrographs were taken using an Olympus® petrographic microscope with DP20 camera. The photomicrographs were analyzed to determine modal percentages of each mineral. This was done using a combination of manual techniques and a scientific image analysis program known as ImageJ. ImageJ program allows for the simplified measurement of grain size as well as the analysis of percentages of each mineral within an image.

As extrusive rocks, both Ballast A and Ballast aggregate particles analyzed had very fine-grained ground masses that made a definite determination of their composition difficult, if not impossible, in thin section. To help determine a more exact composition, the specific gravities of the constituent minerals and the overall specific gravities were used in a system of equations to help estimate the composition of each rock. This required knowing the percentages of one to two minerals within a rock, which was accomplished using the ImageJ program.
Table 2 – Descriptive terms used in petrographic description. Reproduced from Winter (7).

<table>
<thead>
<tr>
<th>Texture</th>
<th>Definition</th>
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<tbody>
<tr>
<td><strong>Grain Size</strong></td>
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<tr>
<td>Aphanitic</td>
<td>Having minerals too fine grained to see with the naked eye</td>
</tr>
<tr>
<td>Phaneritic</td>
<td>Having minerals coarse enough to see with the naked eye</td>
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<tr>
<td>Cryptocrystalline</td>
<td>Having minerals too fine grained to distinguish microscopically</td>
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<tr>
<td>Fine-grained</td>
<td>Having an average crystal diameter less than 1 mm</td>
</tr>
<tr>
<td>Medium-grained</td>
<td>Having an average crystal diameter 1-5 mm</td>
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<tr>
<td>Coarse-grained</td>
<td>Having an average crystal diameter greater than 5 mm</td>
</tr>
<tr>
<td>Very Coarse-Grained</td>
<td>Having an average crystal diameter greater than 50 mm</td>
</tr>
<tr>
<td>Equigranular</td>
<td>Having grains that are all approximately the same size</td>
</tr>
<tr>
<td>Inequigranular</td>
<td>Having grains that vary considerably in size</td>
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<tr>
<td><strong>Form of Individual Grains</strong></td>
<td></td>
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<tr>
<td>Euhedral</td>
<td>Completely bounded by crystal faces</td>
</tr>
<tr>
<td>Subhedral</td>
<td>Having crystal faces that are only partially developed</td>
</tr>
<tr>
<td>Anhedral</td>
<td>Having crystal faces that are entirely absent</td>
</tr>
<tr>
<td><strong>Porphyritic Textures</strong></td>
<td></td>
</tr>
<tr>
<td>Porphyritic</td>
<td>Having approximately bimodal size distribution (usually requires a great difference)</td>
</tr>
<tr>
<td>Megaporphyritic</td>
<td>Having a porphyritic texture that can be seen in hand specimen</td>
</tr>
<tr>
<td>Microporphyritic</td>
<td>Having a porphyritic texture that is visible only under the microscope</td>
</tr>
<tr>
<td>Phenocrystal</td>
<td>A large crystal set in a fine matrix</td>
</tr>
<tr>
<td>Groundmass</td>
<td>The glassy or finer-grained element in the porphyritic texture</td>
</tr>
<tr>
<td><strong>Miscellaneous Textural Terms</strong></td>
<td></td>
</tr>
<tr>
<td>Microlites</td>
<td>Tiny needle- or lath-like crystals of which at least some properties are microscopically determinable</td>
</tr>
<tr>
<td>Trachytic</td>
<td>Consisting of (feldspar) microlites aligned due to flow</td>
</tr>
<tr>
<td>Felty/Pilotaxic</td>
<td>Consisting of random microlites</td>
</tr>
<tr>
<td>Twin/Twinning</td>
<td>An intergrowth of two or more orientations of the same mineral with some special crystallographic relationship between them</td>
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</table>

A final note should be attached to these examinations. Petrography is in most cases, and especially in the case of these samples, a “less exact” science than engineering. Whereas most of the physical properties and test results obtained had specific methods and procedures for determining these values, the petrographic examinations require a certain amount of inference. Accordingly, mineral compositions should be considered estimations.

**PETROGRAPHIC EXAMINATION**

This section contains detailed descriptions of the petrography of both ballast aggregates. This includes percentages of mineral constituents, textural properties, and other relevant descriptive data of the rocks. Finally, representative photomicrographs of each rock are shown. Table 2 above contains definitions of petrographic terms used in the text below. They are reproduced from the text by Winter (7).

**Ballast A**

Ballast A has a porphyritic aphanitic texture. It is composed of 25% white to light pink anhedral alkali feldspar phenocrysts 0.5 to 3.0 mm in size and 0.10% brownish green epidote phenocrysts 0.25 to 4.0 mm in size in a brick red to reddish-brown cryptocrystalline groundmass. Some of the alkali feldspar phenocrysts display Carlsbad twinning. The groundmass has an average grain size of 1 to 10 μm and is composed of 60.41% quartz crystals (45.24% of total sample), 24.91% alkali feldspar crystals (18.66% of
total sample), and 14.69% opaque iron oxides (11.0% of total sample). From this mineralogical examination, Ballast A can be classified as an alkali feldspar rhyolite porphyry. Photomicrographs of Ballast A at 2x and 10x magnification are presented in Figure 8 and Figure 9, respectively.

**Ballast B**

Ballast B has a porphyritic aphanitic texture. It is composed of 15% clear, anhedral alkali feldspar phenocrysts 0.5 to 3.0 mm in size with accessory black, anhedral hornblende crystals 20 to 120 μm in size (0.50% of total sample) in a leucocratic to pink groundmass. Some of the alkali feldspar phenocrysts display Carlsbad twinning. The groundmass has an average grain size of 20 to 80 μm and is composed of 63.55% quartz crystals (53.70% of total sample), 24.62% alkali feldspar crystals (20.80% of total sample), and 10.65% opaque iron oxides (9.0% of total sample). In addition, the sample has approximately 1.0% air voids 20 to 150 μm in size. The porphyritic nature of this rock is not identifiable in hand sample, as the phenocrysts are composed of some of the same minerals of the groundmass (alkali feldspars). From this mineralogical information, Ballast B can be classified as an alkali feldspar rhyolite porphyry. Photomicrographs of Ballast B at 2x and 10x magnification are presented in Figure 10 and Figure 11, respectively.
Figure 8 – Photomicrographs of Ballast A at 2x magnification under (a) PPL and (b) XPL
Figure 9 – Photomicrographs of Ballast A at 10x magnification under (a) PPL and (b) XPL
Figure 10 - Photomicrographs of Ballast B at 2x magnification under (a) PPL and (b) XPL.
Figure 11 – Photomicrographs of Ballast B at 10x magnification under (a) PPL and (b) XPL.
DISCUSSION

Figure 12 is a Quartz-Alkali feldspar-Plagioclase (QAP) diagram, which is used to classify rocks based on their composition, and plots the total composition of Ballasts A and B as well as the composition of their groundmasses. Figure 12 shows that both Ballast A and Ballast B have relatively similar mineralogical composition, and their groundmasses fall nearly on top of one another. The primary difference between the two rocks appears to be in the grain size of the ground mass. This then leaves the question of whether this grain size difference directly affects the aggregate strength, or whether it causes poor particle breakage characteristics (and thus undesirable particle shape properties) which may in turn lead to decreased aggregate strength.

![Figure 12 – QAP diagram of Ballast A and Ballast B](image)

Although single particle crush tests (SPCTs) are not completely independent of particle shape, they are the best indicators of particle strength independent of gradation or shape properties available. Upon examining these tests, Ballast A has statistically higher particle survival strength than that of Ballast B. Thus, from this examination and single particle crush test results, Ballast A has a higher rock strength and more desirable particle shape relative to Ballast B, which is mainly attributable to the smaller grain size of the rock’s groundmass. Furthermore, it is hypothesized that this is due to the increased specific surface area of these grains, which allows for more bonds between grains. This examination lays the groundwork for examination of future potential ballast aggregate sources on the basis of petrography, which can be analyzed relatively inexpensively and quickly when compared to physical strength testing.

CONCLUSIONS

This paper presented a case study to compare two ballast aggregates and demonstrate that petrography is a useful tool for evaluating ballast material quality affecting its performance. After conducting a petrographic examination on the two rhyolite trap rock aggregates, Ballast A and B, Ballast B’s larger grain size was identified as a highlighted feature that may have negatively impacted its performance. From petrographic examination and single particle crush test results, the Ballast A has a higher rock strength and more desirable particle shape relative to Ballast B. Note that Ballast B had also the highest...
flat and elongated ratio, i.e. very slender particle with the potential to break more easily under traffic loading when used in the track. Whereas relying solely on particle shape properties may have led the attempts to re-design a quarry’s aggregate crushing equipment for better particle shape, petrography showed that this aggregate is not suitable for use as railroad ballast due to the larger grain size of the rocks. This was shown through the microscopic examination of the two rocks. This examination lays the groundwork for petrographic evaluation of future potential ballast aggregate sources, which is less expensive and quicker than physical and mechanical strength testing.

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