USDOT Tier 1 University Transportation Center Final Report

NURail2012-MTU-R02

Assessment of Aggregate Sources in Michigan for High Speed Railroad Ballast

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DISCLAIMER

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TECHNICAL SUMMARY

NURail2012-MTU-R02 Final Report September 23, 2014

Title

Assessment of Aggregate Sources in Michigan for High Speed Railroad Ballast

Introduction

The Michigan Department of Transportation (MDOT) is evaluating upgrading of their portion of Amtrak's passenger route that runs from Chicago to Pontiac near Detroit as part of the Michigan Accelerated Rail Program. The MDOT portion of the rail line, referred to as the Michigan Line, was purchased from the Norfolk Southern in 2012. Currently, the rail line handles passenger and freight traffic. An upgrade of the Michigan Line would allow trains to travel at speeds up to 110 mph from Chicago to the Detroit area. To meet this speed requirement, the current track structure will need to be assessed to determine if it can handle the increased dynamic loads associated with higher speed traffic. An important track structure component is the ballast material. The Michigan Line is located in the southern portion of the state where the main aggregate deposits are carbonate rock, which is generally considered a lower quality rock deposit for railroad ballast. The key issue on the replacement of ballast is

cost with the tradeoff being the quality of the ballast material and the distance to the rail line. The primary objectives of this report are as follows: (1) to assess the current MDOT quality specifications for the railroad ballast and to compare them with ballast specifications for higher and high speed rail (HSR), (2) to assess the current aggregate sources in Michigan for HSR ballast and (3) to investigate a carbonate aggregate deposits located in northern Michigan along Lake Michigan that was found to have unique dynamic properties that might make it useful as a HSR ballast.

Based on a review of ballast specifications in the United States, the study found no specific specifications for HSR. The study did find one international ballast specifications for HSR that used the Los Angles (LA) Abrasion test. In general, the study found that the two most common ballast specification tests that most influence the acceptance of aggregate for non-HSR ballast are the LA Abrasion test, which is considered an impact test, and the Micro-Deval test, which is considered an abrasion test. Current MDOT ballast specifications for the LA Abrasion test is at a value not to exceed 40% for all rock types, with a higher percent indicating a lower quality aggregate. MDOT has no Micro-Deval ballast specifications. This is not a common specification for US railroads, but it is a common standard for international railroads. The AREMA LA Abrasion values range between 25 to 40% depending on the rock type. Amtrak has a much stricter LA Abrasion standard of a maximum 18% for all rock types. The European Union (EU) has recently adopted common ballast specifications for all member countries. The EU LA Abrasion specification ranges from12 to 24% depending on the type of railroad but in general uses a value of 24% as a standard. Germany, however, although an EU country, still uses a much lower LA Abrasion limit of 9 to 10% for basalt and 14 to 23% for carbonate rock.

The MDOT LA Abrasion specification of 40% allows approximately 70% of the carbonate sources in Michigan and the surrounding states to be used on MDOT railroad lines. Since there are no MDOT or national ballast standards for HSR, this study applied the Amtrak specifications of a LA Abrasion of 18%, as criteria for the second objective of the study which was to assess the aggregates available in Michigan. The study used the 2012 MDOT Aggregate Inventory to assess the aggregate quarries in Michigan. Based on the LA Abrasion criteria of 18% it was found that no carbonate quarries in Michigan and the surrounding states would be able to meet the 18% maximum on a consistent basis. The study also found that 100% of the igneous and metamorphic sources located in northern Michigan and Canada would be able to meet the 40% criteria while 25% would be able to consistently meet the 18% criteria.

One additional aggregate source that has recently come on line but is not included in the MDOT aggregate inventory is waste rock from the former Groveland Mine located east of Crystal Falls, MI in the Upper Peninsula. The Groveland Mine was an open pit iron mine that operated between the 1950s' and the 1980's. The mine produced a significant amount of waste rock that consisted of hard iron-rich quartzite, with a specific gravity of 3.4 and a LA Abrasion index of 10%. Recently, a company has started to produce aggregate, ballast and armor stone. The armor stone has been approved by the U.S. Corps of Engineers for use on waterway structures. The mine has an active rail line adjacent to the operation.

The vast majority of crushed aggregate in Michigan, however, is from carbonate quarries since three-quarter of the state consists of sedimentary rock. The entire Lower Peninsula and half of

the Upper Peninsula bedrock geology is sedimentary. Due to aggregate problems in concrete pavements in Michigan, Michigan Tech investigated the mechanical properties of aggregate to determine if certain carbonate aggregate performs better in a dynamic environment, such as concrete joints on U.S. Interstate systems. The dynamic properties of the aggregate were assessed using a Split Hopkinson Pressure Bar that can test the strength and stiffness of the carbonate rock at very high strain rates, which is considered to be similar to the dynamic loading of ballast materials during train loading.

The research revealed that limestone aggregate performs much better dynamically than dolomite aggregate. In addition, it was found that one limestone aggregate tested from the Port Inland Quarry in the Upper Peninsula had exceptionally high dynamic strength and stiffness at the level of high quality igneous basalts and trap rocks. The third objective of this research, therefore, was to confirm the dynamic properties of the Port Inland Quarry limestone. The testing revealed that the Port Inland limestone does have high dynamic strength and stiffness that could make it a possible aggregate source for HSR railroad ballast.

Results

The following conclusions were determined in this study:

1. The majority of aggregate quarries in the Lower Peninsula and the eastern half of the Upper Peninsula are carbonate quarries. Igneous and metamorphic quarries occur in the western end of the Upper Peninsula and in Canada.

2. In this study, the Los Angeles Abrasion (LAA) test was used to assess aggregates listed in the MDOT aggregate inventory database for use as a source for ballast material. The database also lists other deposit types such as crushed concrete", blast furnace slag, steel slag and sand & gravel deposits. Only the carbonate and igneous and metamorphic deposits were considered in this study.

3. MDOT has seven specifications used to assess railroad ballast. The most significant specification is the LAA value with is a maximum value of 40%. This is a relatively low LAA value and one of the lowest identified in reviewing major US railroad ballast specifications.

4. According to the MDOT aggregate inventory database, however, 70% of carbonate aggregates in Michigan and surrounding states have a LAA values less than 40% and could be used for railroad ballast. The AREMA LA A value for carbonates is 25%, while Amtrak uses a maximum LAA of 18%. None of the carbonate quarries in Michigan and surrounding states could likely meet a lower 18% LAA specification.

5. All of the igneous and metamorphic quarries listed in the MDOT aggregate inventory database could meet the MDOT LAA specification of 40%, while about 25% could consistently meet the stricter Amtrak specification of 18%

6. The static strength of the Port Inland Quarry limestone was measured to be about 10,500 psi, while its dynamic strength was 33,700 psi. While the static strength is comparable to other limestones, the dynamic strength is significantly higher than found for other limestones or dolomites.

Recommendations

1. The MDOT specification of LLA be less than 40% should be reviewed. While economics of the cost, transportation and replacement will be the main factor in determining the ballast type used, the current specification used by major US railroads and internationally all use a much lower LAA specification.

2. The LAA test is not the only test used to assess ballast material. The Micro-deval and the mill tests are two tests that are being used and should also be considered. We recommend that additional testing be conducted to determine if the dynamic properties of carbonates might indicate that they can be considered for ballast for the Michigan Line HSR.

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Appendix 1 – Final NURail/MDOT Report

Assessment of Aggregate Sources in Michigan for High Speed Railroad Ballast

Final Report

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16. Abstract

MDOT purchased 135 miles of the Norfolk-Southern railroad in 2012 to upgrade for high speed rail travel between Chicago and the Detroit area. An important part of the upgrade is to assess the current quality of the ballast material and to determine if the ballast meets possible high speed rail standards. This report investigated current MDOT ballast standards, other US railroad standards, international standards and if high speed rail ballast standards had been adopted. The Los Angeles abrasion (LAA) standard was used to investigate aggregate sources in Michigan and the surroundings states and Canada. The LAA values used in the study were obtained from MDOT's aggregate inventory database. MDOT's current LAA specification is a minimum of 40%, while Amtrak is 18%. The study found that the current MDOT ballast specifications of LAA of 40% allow most of the carbonate sources in Lower Peninsula to be used. The stricter LAA limit of 18% would not allow most carbonate aggregate source to be used, while 25% of the igneous and metamorphic sources that occur in the Upper Peninsula (UP) and Canada would be able to meet the 18% specification. The study also investigated the dynamic properties of the Port Inland limestone and found that while its LAA would not meet Amtrak standards, its dynamic strength is similar to the static strength of the iron ore waste rock in the UP.

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Table of Contents

List of Tables

List of Figures

Executive Summary

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The vast majority of crushed aggregate in Michigan, however, is from carbonate quarries since three-quarter of the state consists of sedimentary rock. e.g., the entire Lower Peninsula and half of the Upper Peninsula bedrock geology is sedimentary. Due to aggregate problems in concrete pavements in Michigan, Michigan Tech investigated the mechanical properties of aggregate to determine if certain carbonate aggregate performs better in a dynamic environment, such as concrete joints on U.S. Interstate systems, which are dynamically loaded, might perform better than others. The dynamic properties of the aggregate were assessed using a Split Hopkinson Pressure Bar that can test the strength and stiffness of the carbonate rock at very high strain rates, which is considered to be similar to the dynamic loading of ballast materials during train loading. The research revealed that limestone aggregate performs much better dynamically than dolomite aggregate. In addition, it was found that one limestone aggregate tested from the Port Inland Quarry in the Upper Peninsula had exceptionally high dynamic strength and stiffness at the level of high quality igneous basalts and trap rocks. The third objective of this research, therefore, was to confirm the dynamic properties of the Port Inland Quarry limestone. The testing revealed that the Port Inland limestone does have high dynamic strength and stiffness that could make it a possible aggregate source for HSR railroad ballast.

1. Introduction

In 2006, the Federal Railroad Administration (FRA) designated the rail corridor between Chicago and Detroit as a High Speed Rail (HSR) corridor and provided funds to investigate needed infrastructure improvements to allow faster and more frequent passenger train service along this rail corridor. In 2012, the U.S. Surface Transportation Board approved the Michigan Department of Transportation (MDOT) request to acquire and improve the 135-mile Norfolk & Southern (NS) line from Kalamazoo to Detroit to allow Amtrak's Wolverine Service to run at speeds up to 110 mph.

The Accelerated Rail Program corridor is approximately 300 miles long and begins in Chicago on NS track to the Indiana/Michigan border at Porter, Indiana. From Porter to Kalamazoo, Michigan the track is owned by Amtrak. The remaining135 miles to Detroit/Pontiac were acquired from the NS by MDOT in 2012. Currently, Amtrak runs its passenger lines at speeds up to 110 mph over the corridor. MDOT's goal is to upgrade Michigan section of the railroad to be able operate at speeds up to 110 mph. An important aspect of the evaluation and upgrade process will be the assessment of the rail track structure, which consist of rail, ties and ballast materials.

Currently, Michigan sections use carbonate (limestone or dolomite) rock as ballast. While carbonate rocks are commonly processed for use as ballast on many railroads, they can be problematic when compared to other more durable rocks such as igneous and metamorphic rocks. Carbonate rocks, however, are readily available in the Midwest and especially in southern Michigan along the route.

The main objectives of this study are three-fold. The first objective was to investigate current specifications for ballast specifications regular rail lines and for HSR. The second objective was to investigate aggregate sources in the state of Michigan and surrounding states that could be used to produce ballast for HSR. The third objective was to investigate the dynamic properties of the Port Inland Quarry carbonate for possible use as HSR ballast. Although Michigan is one of the most geologically diverse states in the United States, three-quarters of the state consists of sedimentary rocks. While the northwestern portion of the state consists primarily of pre-Cambrian igneous and metamorphic rocks, the remaining three-quarters of the state consists of sedimentary rock where carbonates are the primarily rock type used for aggregate and ballast production.

The study was divided into the following six tasks:

1. Investigate MDOT as well as national and international ballast specifications for HSR.
2. Review aggregate sources in Michigan via the MDOT aggregate inventory database and identify sources that have a potential of meeting ballast specifications.
3. Investigate aggregate sources from the iron mines located in northern Michigan for use as a ballast material.
4. Study the dynamic properties of the carbonate of a specific carbonate quarry to determine if these properties might be indicate that the carbonate might work as a ballast material. The Port Inland Quarry, located on the shore of Lake Michigan in the Upper Peninsula with both rail and dock facilities, was selected for this analysis.

5. Evaluate all data collected in tasks one through six and assess the potential of aggregate produced in Michigan to be used in a high speed rail application.

6. Complete a final report detailing the analysis and data collected in the project. The final report will provide conclusions, limitations and recommendations for future work.

The eight tasks were conducted and reported in the following four activities:

The first activity was to conduct a literature review on the various issues involved in specifying ballast materials. This included investigating the many parameters that affect the behavior of ballast material. In addition, ballast specifications from MDOT and other railroad agencies both in the United States as well as internationally were reviewed. An important aspect of this review was to determine if ballast specifications had been developed for HSR systems.

The second activity was to examine the Michigan Department of Transportation (MDOT) aggregate inventory database for the aggregate sources in Michigan that meet ballast specifications for HSR.

The third activity of this study investigated aggregate sources from the iron mines located in northern Michigan. The iron ore in northern Michigan consists if a very hard, strong rock, and is considered an excellent source for railroad ballast, especially for HSR.

The fourth activity of the study was to investigate a carbonate limestone aggregate from the Port Inland Quarry located in the southern part of the Upper Peninsula with shipping and rail facilities on Lake Michigan. Aggregates from the Port Inland Quarry were included in a research project at Michigan Tech conducted in 2002 dealing with the dynamic fracture of aggregates used in Portland cement concrete (Vitton et al, 2002). This research investigated both the static and dynamic strength and stiffness characteristics of a broad range of aggregates. While the Port Inland Quarry aggregate had similar static strength and stiffness characteristics as other carbonates deposits, its dynamic characteristics were significantly higher and in the same range as basaltic rock from Portage Lake Lava series and the Ontario Trap Rock gabbro.

2. Literature Review

A literature review was conducted to investigate research on aggregates used for railroad ballast and HSR lines. This review was conducted in four parts. The first part is a general review of research conducted on rail ballast identifying important issues that concern the selection and use of rail ballast. The United States association that conducts the majority of research and makes recommendations on ballast specification is the American Railway Engineering and Maintenance-of-Way Association (AREMA). The second part of this section, provided a review of important issues that AREMA identifies concerning rail ballast. It should be noted that while AREMA is composed of the major railroads in the United States, many of the major railroad companies in the United States also conduct ballast research separately from AREMA, e.g., Union Pacific has an active research effort on ballast. The review, however, is limited primarily to the information provided by AREMA. Following this, a short review is provided on issues found dealing with the selection of rail ballast for HSR. This section is relatively short

as there has been limited research on this topic. Nonetheless, a number of important issues, while not well researched, are presented. The final part of this section provides the ballast specifications for the following organizations: (1) MDOT, (2) AREMA (3) Amtrak (4) Union Pacific and (5) international standards.

2.1 Railroad Ballast General Discussion

Railroad ballast is an integral part of a railroad's roadbed and is schematically illustrated Figure 1. The railroad track consists of the following components:

1) Steel rails and ties (sleepers), with the ties holding the rails in place,
2) Ballast and sub-ballast, which is designed to handle the majority of the static and dynamic loads induced from train loading and requires periodic maintenance and replacement,
3) Blanket or subgrade embankment, which is generally made with local soils and rock and considered permanent after construction, and
4) The subsoil or natural ground in which the entire railroad structure in built upon.

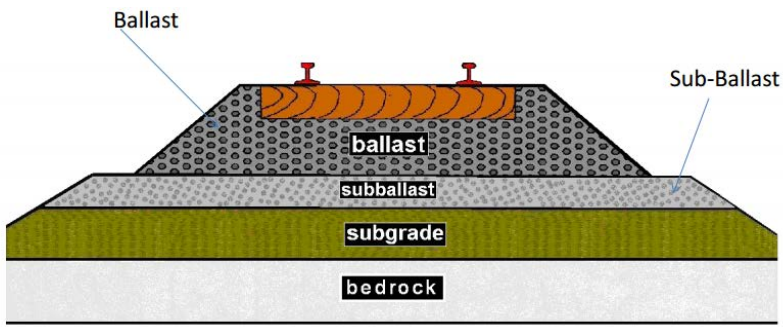


Figure 1 Cross-section of a typical railroad structure.

The early days of the railroad industry used a variety of materials for ballast mostly generated from local sources close to where the railroad line was being constructed. The first systematic analysis of railroad ballast in the United States was undertaken by the American Society of Civil Engineers (ASCE) through a special committee on "Stresses in Railroad Track". The committee was comprised mainly of members of the American Railroad Engineering Association and its first progress report was issued in 1918. The initial focus of the research concentrated on a theoretical model of stresses in the rail track system, which modeled the track system as a linear-elastic structure. They soon realized, however, that the assumption of the track structure being linearly elastic was not adequate when they compared their theoretical results to stresses measured in actual loading conditions. The research was then refocused to a more experimental basis where extensive field testing on standard railroad track was conducted to better understand the actual loads which included the variability of conditions experienced in the field. The second progress report, authored by the ASCE committee under the chairmanship of A. N. Talbot (1919), was issued in 1919. This report became instrumental in the basic understanding of ballast material performance and is still widely referenced today.

This report produced three important findings. First, the stresses in the railroad ballast increase with train speed. Second, the stress distribution beneath the sleepers is independent of ballast types such as "broken rock", sand or finer-grained materials. This finding lead directly to the determination of the depth of ballast required to more fully accommodate train loads so as to maintain a tolerable load level on the subgrade and subsoil soils to limit deformation. And third, while sand would act in a similar fashion to "broken rock" in handling loading stresses from a train, it did not have the strength or bearing capacity to prevent lateral movement of the ballast. Thus, this finding suggested that "coarser", "rougher", i.e., larger and more angular types of ballast would better carry a greater ultimate load. In effect, the third finding resulted in using all ballast having to 100% crushed with larger size aggregate ballast and higher frictional strength, which in general would need to be produced at a quarry where competent rock can be crushed and sizes to meet certain size-specifications.

Through 1975, the general design requirements for ballast for conventional railroad track were generally based on satisfying the strength criteria of the individual track components and the depth of the ballast to minimize stresses on the subgrade (Robnett et al. 1975). After 1975, additional factors and design considerations were added when designing for railroad track ballast. These factors and design considerations include the following (Doyle 1980):

1) Provide a firm uniform bearing surface for the sleepers (ties) to transmit the train loads into the ballast material at a depth to minimize the loading to the subgrade to a tolerable

level.

2) Provide the necessary vertical, lateral and longitudinal stability to the track structure to hold both the track and ballast in place as a train passes.
3) Allow track maintenance operations to make corrections to the track surface as well as realignment errors.
4) Provide adequate drainage so that the ballast remains dry.
5) Prevent vegetation from growing on the track structure.

As train speeds and weight increased, other factors have become important in the performance of ballast. One of the more important factors is known as ballast fouling that results from particle-to-particle breakage caused by higher train loads. According to Chrismer (1995), who conducts research for the Association of American Railroads at the Transportation Technology Center, Inc. (TTCI) in Pueblo, CO, the main source of ballast fouling was caused by the mechanical wear of the ballast through repeated train loading. He states,

> "*That the ballast material quality has a great influence upon ballast life and those methods to determine the resistance to such breakdown mechanisms also becomes very important." He further states "the selection of the economical ballast material depends upon such considerations as purchase price, material quality, hauling distance from the quarry, and track renewal methods to name a few of the more important factors. However, the issue of material quality and how it affects ballast life in track has been one of the most difficult to resolve."*

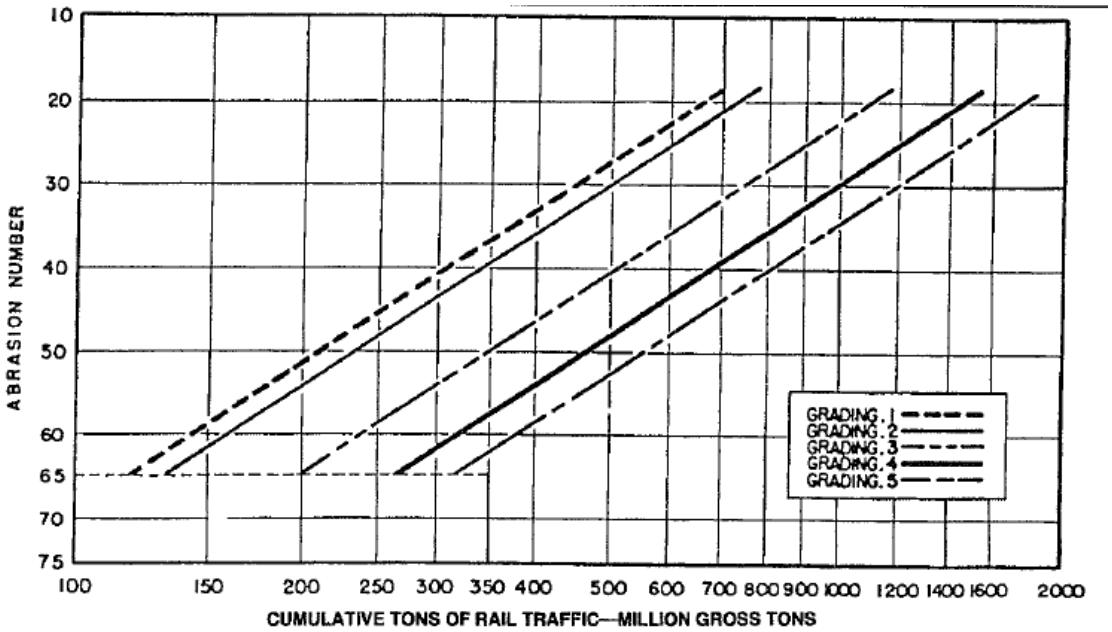
Chrismer (1997), in a later research paper, states that current specified laboratory tests for ballast may not be a reliable indicator of actual ballast breakdown because limitations of the tests do not sufficiently duplicate the environment and breakdown mechanisms. A small number of in-service durability tests of ballast materials have shown certain laboratory tests to be better indicators than others at predicting ballast life and performance.

The standard laboratory test used in the United States to assess railroad ballast quality is the Los Angeles Abrasion (LAA) test. This test is a combined impact-abrasion test that uses steel balls in a rotating steel barrel to impact and abrade a *dry* ballast material. The amount of breakage as determined by the decrease in particle size or loss is the main assessment value for this test. The Micro-Deval test, which was developed in France, is also used to assess ballast quality and uses a *wet* abrasion test with much smaller steel balls in a plastic container (barrel). It is used extensively in Canada and Europe for both rail ballast assessment as well as for general aggregate use for roads. For example, the Micro-Deval test is used in Britain for assessing rail road ballast quality due to its wetter climate and lighter train loads.

Chrismer, however, did not find a good correlation between the LA Abrasion and Micro-Deval tests and ballast performance in the field. He instead proposed a new test called a Mill Abrasion Test, which was developed by himself and Ernest Selig at the University of Massachusetts, (Chrismer and Selig 1994). This test is a combination of the LA Abrasion test and the Micro-Deval test. The results of the Mill Abrasion test are reported in terms of an A_N number for each ballast type and gradation. The A_N number is equal to the LA Abrasion results for a ballast material plus five times the results of the Mill Abrasion test for the same ballast material. Using the Mill Abrasion parameter and a mechanistic computer model Chrismer and Selig (1994) developed a computer simulation program called BALLAST2.

This computer simulation model generates a hypothetical life-cycle cost estimate for railroad ballast based on the A_N number and the amount of freight tonnage per year given in terms of million gross tons per year (MGT). Results from the BALLAST2 computer model for a given range of ballast quality based on the A_N number are presented in Figure 2. The results are in equivalent annual costs (EAC) per ton, based on 1995 costs. The average life-cycle cost from this study was determined to be $4,700 per track mile per year. These results indicate that as the quality of the ballast increases based on the A_N number, the overall life-cycle cost decreased. While this is an obvious outcome, the results do provide an economic assessment so what the penalty for using lower quality aggregates. This is an important outcome as not all railroad lines are located near high quality ballast.

Another study by Chrismer (1997) investigated the cumulative rail traffic tonnage for various A_N parameters based on various ballast gradations. The results of this study are shown in Figure 3. Again as the A_N increases, the total freight tonnage a given ballast gradation can accommodate prior to replacement also increases for a given ballast gradation. The study investigated five gradations identified as numbers 1 through 5. Typical main line ballast gradations would be similar to No 3 and No. 4 gradations, while No. 5 would be used for rail yard ballast. Gradations 1 and 2 are seldom used. The basic difference in these gradations is that as the gradation number increases the overall size of the ballast decreases but with the No. 4 gradation having a broader distribution of sizes than the No. 3 gradation. Thus, according to Figure 3, the No. 4 gradation should be able to handle a higher traffic load then a No. 3 gradation.



NOTE: Developed for tangent track with 7 in. of ballast below tie. A small amount of contamination from outside sources has been taken into consideration.

CAUTION: Excessive handling of ballast materials in the upper range of abrasion numbers may generate fines which will reduce the applicable cumulative tones of rail traffic.

Figure 2 Ballast life cycle cost with Mill Abrasion Number and traffic tonnage (Chrismer and Selig, 1994).

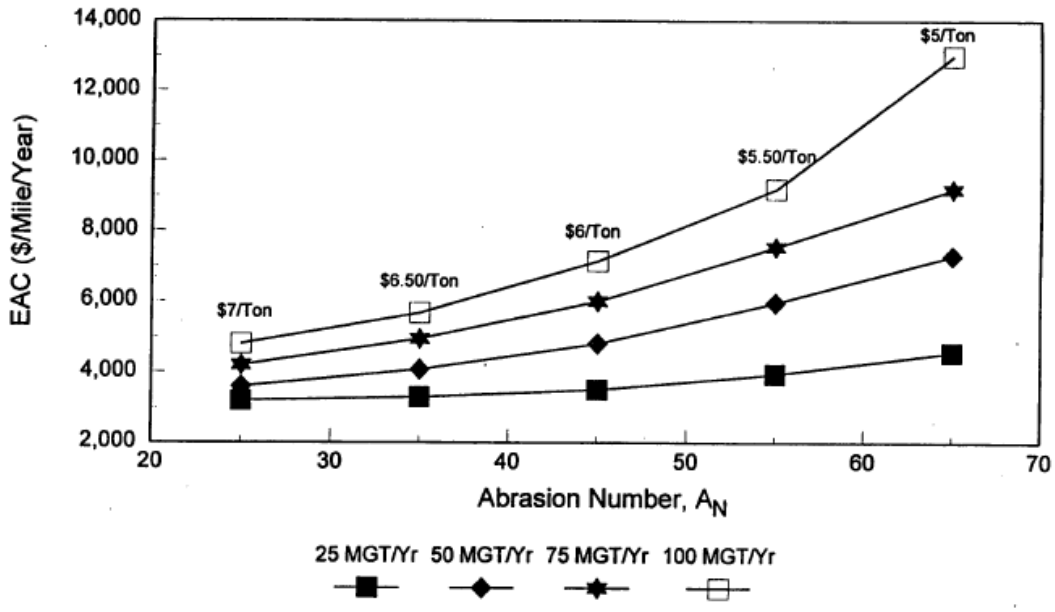


Figure 3 **Mill Abrasion Number (A_N) versus cumulative tons of rail traffic for various ballast gradations (Chrismer 1997).**

2.2 American Railway Engineering and Maintenance-of-Way Association (AREMA) Ballast Specification

The main association that represnts American railroads is the American Railway Engineering and Maintenance-of-Way Association (AREMA). AREMA was formed on October 1, 1997, as the result of a merger of three engineering support associations, namely the American Railway Bridge and Building Association, the American Railway Engineering Association and the Roadmaster's and Maintenance of Way Association, along with functions of the Communications and Signals Division of the Association of American Railroads. The prime mission of AREMA "*is the development and advancement of both technical and practical knowledge and recommended practices pertaining to the design, construction and maintenance of railway infrastructure*." All major railroads that operate in the United States are members of AREMA. Part of the consolidation of these associations was to unify the many aspects of their missions, which in many cases overlapped. Also in 1997 AREMA published the AREMA Maual for Railway Engineering. Chapter 1 of the manual is titled "Roadways and Ballast" and provides recommendations dealing with railroad track such as the roadbed, ballast, natural waterways, fences, tunnels, etc. Section 2 of Chapter deals specifically with ballast and sub-ballast. A key aspect of this section is to provide recommendations on acceptable material quality and property requirements. It should be noted, however, that the recommendations provided in the AREMA manual are only advisory in nature. Individual railroads will have their own specific standards to meet specific conditions that each railroad line encounters. In general, most railroads follow relatively similar ballast material specifications standards as provided in the AREMA specifications but with different values for the various criteria. Details of the key AREMA ballast specificatiaons are provided in a later section. The final portion of AREMA's Chapter 1, Section 2 provides a disscussion on important issues concerning ballast material. A summary of these issue as are as follows:

First, while Section 2 was published in 1988, it states that efforts to produce a definitive ballast performance specification is not complete but that AREMA, through its research efforts, are approaching their goal. Clearly, since 1988 a significant amount of research has been conducted by TTCI as noted above and other researchers but as of 2013 this work has not yet been incorportaed into the AREMA Maual for Railway Engineering. For example the research into the Mill Abrasion test by Chrismer (1995 1997) is not included in the 2013 version of the AREMA manual.

Second, the key criteria discussed in AREMA's Chapter 1, Section 2 for selecting a ballast material is that it is important to consider its field performance and behavioral characteristics regardless of how the ballast material was selected via specific test specifications. The two most important criteria for ballast are (1) the ability to drain and (2) to maintain its internal strength throughout the ballast life.

Third, the most commonly used rock deposits used in the United States are as follows:

- Granite
- Traprock
- Quartzite
- Limestone
- Dolomite
- Blast Furnace Slag

These rock deposits are defined in the railroad manual. For example, granite is defined as "*a plutonic rock having an even texture and consisting of chiefly of feldspar and quartz*." While this definition clearly defines a granite, it can also include other acidic rocks such as a andesite, granodiorite, or a monzonite. A traprock, on the other hand, is defined as "*any dark-colored non-granitie hypabyssal or extrusive rock*." A hypabyssal is further defined as "*pertaining to igneous intrusive or to a rock of that intrusive whose depth is intermediate between that of a plutonic and the surface*."

Fourth, a "preferred ballast" material should have the following characteristics:

- *Be a clean and graded crushed stone aggregate with a hard dense, angular particle structure with shape corners and a cubical fragments with a minimum of flat or elongated pieces.*
    - *The clean and angular nature of the ballast will promote drainage and particle interlocking giving the ballast internal strength.*
    - *Minimizing flat and elongated particle will minimixe settlement of the ballast during loading. The flat and elongated particles tend to crush easier thus promoting settlement of the ballast.*
- *The ballast must have high wear and abrasive properties to withstand dynamic loading and prevent excessive degradation.*
- *The ballast material must have a sufficient unit weight to prevent ballast material from being moving and possibly being ejected from the track structure from the dynamic loading from a train. When ballast is ejected from the tract structure it is generally known as "flying ballast".*
- *The ballast must have high resistance to temperature changes, chemical attack, have a high electrical resistivity, and low absorption propoerties.*
- *The ballast must be free from cementing properties caused by the degradation of the ballast material. Cementing causes the following problems:*
    - *Reduced drainage*
    - *Reduced resiliency*
    - *Re-distrubution of stresses within the ballast resulting in unequal roadbed deformation.*
    - *Interferes with track maintenance since the cemented ballast will be more difficult to remove and replace.*
- *The ballast specifications provided in the AREMA manual does not limit the use of other potential aggregates that might be considerd for ballast as long as the aggregate used is tested in accordance with the specifications and is approved by the enginer or purchaser.*
- *A final consideration for all ballast material, however, is that the engineer should be warned that material which tends to create fines will fill the ballast voids and can limit drainage. This is termed "fouling" and is known to be a problem with the fines generated from carbonate sources, which have a tendency to also cement particles.*

2.3 HSR Ballast Issues

The move to HSR will result in additional technical challenges for the design and specification of railroad structures. A primary issue will be the increase speeds will result in larger "*dynamic loading*" to the track structure. Talbot (1919) showed experimentally that as train speeds increase the loads will correspondingly increase on the railroad bed structure. Li and Selig (1998) determined that at a train speed of approximately 160 miles per hour (mph) that the dynamic loads will be 2.45 times larger than the train's static load. Recent modeling using dynamic finite element techniques by Quinn et al. (2010), however, indicate that as rail speed increase beyond 160 mph the "*rate of increase*" decreases to where a train moving at 250 mph the dynamic load will equal the train's static load. This research, which used field measurements and dynamic finite element modeling, also suggests that for a train moving at 160 mph the dynamics loads are about 1.2 to 1.3 times greater than the train's static loads as compared to 2.45 determined in the Li Selig study. For the Michigan Line this research would still indicate that as the train speeds increase from their current speeds up to 110 mph, the dynamic loading on the ballast will also increase, although not at the magnitude as suggested by Li and Selig. The increase in train speed nonetheless will reduce the life of the ballast material and will increase the maintenance cost of the Michigan Line.

A second issue will be that stresses and deformations of the track structure will also increase with train speed. This will especially be critical for any deformation of the track or on critical curvature section where higher speeds will result in higher stresses on the train itself.

A third issue is ballast migration for super elevation track sections with a high cant. According to Browness et al. (2007) that on elevated track sections during loading the track sleepers rotate about the low rail end and then move towards the high rail end during loading and unloading. Due to the shape of the sleeper (ties), ballast moves vertically downward during loading while is pushed upward during unloading. The net effect of the movement, however, is to cause the ballast to move towards the low end of the track causing an uneven distribution of ballast under the tracks.

A final issue is the problem of flying ballast. Due to the increased speed of the train additional vibration are generated that can cause individual ballast particles to be ejected, i.e. flying ballast. Research by Quinn et al. (2010) investigated both mechanical forces and aerodynamic forces generated by high speed trains and found that neither force individually would result in an increase in ballast flight. They did find, however, that a combination of these forces could in fact result in an increase in ballast flight.

2.4 Railroad Ballast Specifications

While the ballast issues discussed above for high speed have been investigated and report to various degrees, there has only been limited research conducted on modifying existing ballast specifications to meet these higher demands on the ballast. This study reviewed the ballast specifications from MDOT, AREMA, Amtrak and Union Pacific railroads and a limited number of international standards. These ballast specifications are reviewed in the following sections.

2.4.1 MDOT Railroad Specifications

Current standards for railroad ballast in Michigan are provided in MDOT Standard Specifications for Railroad Work (2006) - Division 3, Section 30. The complete specifications are provided in Appendix A. MDOT has seven specifications used to qualify aggregates for use as ballast. A summary of the main

performance specifications are provided in Table 1, while the ballast gradation specifications are provided in Table 2.

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Table 1 MDOT railroad ballast specifications.

Test	Standard	Specification Value
LA Abrasion	ASTM C131	Not to exceed 40%
Crushing	-	100% Crushed
Unit Weight	ASTM C29	Test must be conducted but no specified unit weight specified
Loss by Wash	ASTM C117	Not to exceed 2%
Soundness	ASTM C88	Sodium: 5 cycles with no more than 12% loss Magnesium Sulfate: 5 cycles with no more than 18% loss
Flat or Elongated	ASTM D4791	Ballast retained on 3/8: Ration of 5:1 should not exceed 5%
Soft Particles	Michigan Test Method 110	Not to exceed 5%

Table 2 MDOT gradation specification for railroad ballast.

		Amount Finer Than Each Sieve Percent by Weight							
Size No.	**Nominal Size (Inches)**	**2 1/2"**	**2"**	**1 1/2"**	**1"**	**3/4"**	**1/2"**	**3/8"**	**#4 Sieve**
4A	50 - 19	100	90 - 100	60 - 90	10 - 35	0 - 10	–	0 - 3	–
4	38 - 19	–	100	90 - 100	20 - 55	0 - 15	–	0 - 5	–
5	25 - 9.5	–	100	100	90 - 100	40 - 75	15 - 35	0 - 15	0 - 5

2.4.2 AREMA Specifications

The AREMA railroad ballast specification were the most detailed of the specifications reviewed. Unlike the MDOT ballast specifications, however, the AREMA specifications have separate specifications for seven different aggregate types commonly used in the United States. The recommended specifications are provided in Table 3 and the recommended gradations are provided in Table 4.

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Table 3 AREMA recommended railroad ballast specifications.

Ballast Material								
Property	**Granite**	**Traprock**	**Quartzite**	**Limestone**	**Dolomite Limestone**	**Blast Furnace Slag**	**Steel Furnace Slag**	**ASTM Test**
% material Passing No. 200	1	1	1	1	1	1	1	C 117
Minimum Bulk Specific gravity	2.6	2.6	2.6	2.6	2.65	2.30	2.90	C 127
Absorption %	1	1	1	2	2	5	2	C 127
Clay lumps and Friable particles %	0.5	0.5	0.5	0.5	0.5	0.5	0.5	C 142
LA Abrasion Degradation %	35	25	30	30	30	40	30	C 535[1] C 131[1]
Soundness (Soundness Sulfate) 5 cycles %	5	5	5	5	5	5	5	C 88
Flat and/or elongation %	5	5	5	5	5	5	5	D 4791

[1] Gradation containing particles retained on 25 mm (1 inch) sieve shall be tested by ASTM C 535. Gradations with 100% passing on 25 mm sieve shall be tested by ASTM 131. Use grading most representative of ballast material.

Table 4 AREMA recommended railroad ballast gradations.

Size No. (see Note 1)	**Nominal Size Square Opening**	**Percent Passing**									
		3”	**2 ½”**	**2”**	**1 ½”**	**1”**	**¾”**	**½”**	**d”**	**No. 4**	**No. 8**
24	**2 ½” – ¾”**	100	90-100		25-60		0-10	0-5	–	–	–
25	**2 ½” – d”**	100	80-100	60-85	50-70	25-50	–	5-20	0-10	0-3	–
3	**2” – 1”**	–	100	95-100	35-70	0-15	–	0-5		–	–
4A	**2” – ¾”**	–	100	90-100	60-90	10-35	0-10	–	0-3	–	–
4	**1 ½” – ¾”**	–	–	100	90-100	20-55	0-15	–	0-5	–	–
5	**1” – d”**	–	–	–	100	90-100	40-75	15-35	0-15	0-5	–
57	**1” – No. 4**	–	–	–	100	95-100	–	25-60		0-10	0-5

Note 1: Gradation numbers 24, 25 3, 4A and 4 are main line ballast materials. Gradation 5 and 57 are yard ballast materials

2.4.3 Amtrak Ballast Specifications

Amtrak has the following five ballast performance specifications: (1) deleterious substance percent, (2) flat and/or elongation percent, (3) water absorption percent, (4) LA Abrasion percent, and (5) soundness. Table 5 provides the values for each of these ballast specifications.

Table 5 Amtrak ballast specifications.

Property	Percent by Weight	ASTM Test Method
Deleterious Substance:		
Material Finer than No. 200 Sieve	1	C 117
Clay Lumps and Friable Particles	0.5	C 142
Percent by Weight Flat and/or Elongated Particles	5	Amtrak
Water Absorption	1	C 127
LA Abrasion Maximum Percent	18	C 535
Sodium Sulfate Soundness	5	C 88

2.4.4 Union Pacific Ballast Specification

The Union Pacific Railroad uses ten ballast performance specifications, including both the Mill Abrasion and LAA tests.

Table 6 Union Pacific ballast performance specifications.

Property	Value	ASTM Test
Percent Material, Passing No. 200 Sieve	0.5	C 117
Bulk Specific Gravity	2.6	C 127
Absorption, Percent	0.5	C 127
Mill Abrasion Number, Percent	40	No ASTM Standard
Los Angles Abrasion, Percent	25	C 535 (for aggregate 1” and larger)
Soundness (Sodium Sulfate) 5 cycles, Percent	2	C 88
Flat and/or Elongated Particles, Percent	5	D 4791 or USACE CRD-C119
Plasticity Index Fines, Percent	NP	D 4318
Total Sample Liquid Limit, Percent	25	
Total Sample Plasticity Index, Percent	6	

2.4.5 International Specifications

The main international standard for railroad ballast reviewed in this study was the British Standard EN 13450:2002. This standard is being adopted by the European Union (EU) countries but it is unclear, however at this point in time, whether these standards have actually been adopted. Individual EU

countries still list individual rail ballast standards. Many of these standards, however, are very similar to the AREMA standards and use many of the same test methods.

The European Standard (EN 13450) standards use a number of ballast specification test to assess the quality of ballast with the two most common tests being the LA Abrasion test (LAA), which is considered an impact test, and the Micro-deval test (MDE), which is considered an abrasion test.

The European Standard (EN 13450) test values are provided in Appendix B. The LAA values range from 20 to 24%, with 24% being the general requirement. As noted above, however other EU countries still list separate ballast specifications. The northern European countries, Sweden, Finland and Norway use the LAA test. France uses a combination of the European Standard (EN 13450), the LAA test, and the MDE test to designate track speed. France and the northern European countries make no distinction between rock types for their standards. French ballast specification, however, do provide a separate LAA for HSR lines with a value not to exceed 17%.

3. Project Methodology

The remaining study was conducted in five phases. The first phase investigated the MDOT Aggregate Inventory database, which provides current aggregate test data used in pavements structures in Michigan. The second phase investigated the MDOT railroad ballast specification as well as other sources within the United States and internationally to assess a ballast specification for use on HSR. The third phase then applied a *potential* HSR ballast specification to MDOT Aggregate Database to determine how many quarries Michigan would meet this potential specifications. The fourth phase investigated the waste rock piles located in the Upper Peninsula (UP). The iron ore and associate host rocks at the UP iron mines consist of hard durable metamorphic rock that has exceptional strength and abrasion resistance. For example, the iron mines in Northern Minnesota produce a similar waste rock that is used extensively in Minnesota as a ballast material and has been used in Michigan for ballast material.

Since the large majority of aggregate deposits in Michigan that could produce railroad ballast are from carbonate deposits, the fifth phase investigated the dynamic properties of a limestone quarry in Northern Michigan, the Port Inland Quarry. Previous research at Michigan Tech on the dynamic fracture characteristic used in Portland Cement Concrete (PCC) (Vitton et al. 2002) discovered that the Port Inland limestone had significant dynamic strength and stiffness at about the same level as igneous basalt. While carbonates are used as ballast in Michigan, there are generally not considered a good ballast material due to their ability to degrade and generate fines that foul the ballast and reduce the drainage and overall strength of the ballast.

3.1 MDOT's Aggregate Inventory Database

MDOT maintains an aggregate inventory database for aggregate materials that MDOT uses primarily for assessing aggregates for pavements structures, although the inventory has other uses beyond pavement structures. The database is referred to as the "Aggregate Source Inventory Database & Bituminous Mix Design Nomograph Guide", which can be accessed by the public via the web. The inventory maintain test data conducted by MDOT for the 83 counties in Michigan as well as four states, Ohio, Indiana,

Illinois and Wisconsin and Canada. Not all of the data for each quarry listed in the database is current. Some of the quarries listed in the inventory are not active. The inventory maintains, however, still maintains this test data in the event the quarry reopens. As a rule the aggregate must be tested before being used on a MDOT project if the data is older than five years. In addition, not all quarries have the same tests conducted.

The inventory is grouped into the following primary deposit types:

1. Blast Furnace Slag (BFSLAG)
2. Crushed Concrete (CC & CRSH CONC)
3. Igneous and Metamorphic (IG/MET)
4. Quarry (Quarry) – Generally carbonate rock that are blasted and crushed
5. Sand & Gravel (SD/GR)
6. Steel Furnace Slag (SFSLAG)

The three primary tests conducted for most quarries include the LA Abrasion (LAA) test, a Freeze-thaw test and the Aggregate Wear Index (AWI) test. An additional test conducted on certain aggregates such as blast furnace slag is the specific gravity test. An EXCEL file of the current database inventory was obtained from MDOT and used to search all quarries for their test values.

It should be noted that the freeze-thaw test and the AWI test are specific test to MDOT and deal specifically with coarse and fine aggregate. The freeze-thaw test is for aggregates used in concrete pavements, while the AWI is an important test for asphalt pavements. MDOT's freeze-thaw test follows ASTM C 666 standard but modifies it to adapt to particular requirements for preparation and testing of the specimens. The AWI test, on the other hand, is used only in Michigan; no other state has a similar test. The AWI test measures the ability of a course aggregate to "polish" from tire traffic. An aggregate that polishes would not be a quality aggregate for the top course in an asphalt pavement. Aggregates that don't polish would still wear but maintain a frictional surface.

Both test could possibly be used to also assess ballast aggregate in the future. The most applicable test would be the freeze-thaw test. The AREMA ballast specification, for example, use the percent absorption test (ASTM C 127) as a measure of frost susceptibility of the ballast. Low values of absorption (water) would indicate that the aggregate is most likely not frost susceptible. A key design issue as discussed above for railroad ballast, however, requires that the ballast have adequate drainage and remain relatively dry. Thus, the frost susceptibility of the ballast while still an issue become less important if good drainage is maintained and fouling does not become an issue.

While all of the ballast specifications are important, the LAA value appears to be the critical selection parameter for ballast selection. That is, if an aggregate can't meet the LAA requirement than the remaining parameters become mute. Therefore, the LAA test was used for aggregate selection from quarries in Michigan and surrounding states and Canada. It should be noted that in general, carbonate aggregates tend to have much higher LAA test values, i.e., poorer quality, than igneous and metamorphic rocks. In addition, there tends to be a fair amount of variability when testing carbonates from the same quarry. It is not uncommon for a carbonate quarry to meet a specific LAA specification one time and not another.

3.2 Selection of Ballast Specifications for High Speed Rail

As noted in the literature review, there are no national ballast specifications for HSR in the United States. The only HSR ballast specification found was in France where a LAA of 17% specification is used for all rock types. This is close to the Amtrak specification of 18%. The current MDOT LAA specification is 40%. Since Amtrak will operate the HSR passenger service over the Michigan Line, this study investigated ballast sources at both the 40% and 18% limits, with the implied assumption that the 18% could be a HSR requirement.

3.3 Assessment of Iron Mine Waste Rock Piles in the Upper Peninsula

The western Upper Peninsula (UP) consists primarily of Precambrian igneous and metamorphic rocks. A key mining industry in the UP is the iron mines which mined iron ore from five different geologic basins in the western UP. The iron ore, while sedimentary in origin, has been extensively metamorphosed resulting in a very hard competent rock. Uniaxial compression strength tests on iron ore formation rock from the Menominee Basin and the Marquette Basin were reported in two MDOT reports (Vitton 2002 and Vitton 2008) to be in the range of 30,000 to 35,000 psi. As a comparison, the estimated strength of concrete from a “MDOT - four bag mix” is in the range of 4,000 psi. The ore and its waste rock is not only strong but highly abrasive, which makes it’s a good material for railroad ballast.

The only operational iron mining operation in the UP is Cliffs Natural Resources located in Ishpeming, MI. Cliffs and has dock facilities on Lakes’ Superior and Michigan as well as its own rail system accessing both port facilities. There were, however, hundreds of iron mining operations in the western UP all with waste rock piles. Recently, a company associated with the former Groveland Iron Mine, located east of Crystal Falls MI in northern Dickerson County, opened an a crushing and aggregate supply operation utilizing the waste rock piles from the mine. This operation, however, is not listed in the MDOT inventory.

3.4 Testing the Dynamic Properties of Port Inland Quarry Limestone

3.4.1 Introduction to Dynamic Testing

Carbonate rock, which include limestones and dolomite, tend to be problematic due to their lower strength, higher LAA test numbers and freeze-thaw problems. The primary concern for railroads is material wear and the generation of fines. A research study was conducted by MDOT (Vitton et al, 2002) investigated the dynamic strength and characteristics of aggregates used in PCC pavements. This investigation studied a number of common aggregates from around the state of Michigan, Ohio and Canada, including igneous, carbonate and blast furnace slag materials. Seven different carbonates (three limestones and four dolomites) were studied. The investigation found that while the static properties of the carbonates are relatively similar for all carbonates, their dynamic characteristics are noticeably different, with the limestone aggregate showing much higher dynamic strength and stiffness than dolomites. In general, it has been found that for most materials (not all) the material's dynamic properties are generally different than their static properties, with the materials strength and stiffness increasing with an increase in the dynamic loading rate. This property is known as "*strain rate sensitivity*". The most significant increase in dynamic properties was found to occur with limestones, especially from the Port Inland Quarry located in the UP.

As discussed in the literature section above, ballast is used to dissipate the stresses from train loading, minimizing the loading on the subgrade. Talbot (1919) considered the train loading as dynamic loading of the ballast and also recognized that as train speeds increased so do the stresses on the ballast. Research by Li and Selig (1998) indicated that at 160 mph the increase in loading on the ballast is 2.45 times that static weight of the train. Later research by Quinn et al. (2010) indicated that it was lower at about 1.25. In either case, the research indicates that as train speed increase so does the dynamic loading. Consequently, as part of this study the dynamic strength of the Port Inland limestone was further investigate on larger samples, similar in size to ballast. The samples tested in the MDOT RC-1415 report were significantly smaller with diameters on sample one half inch in size versus one and half inches in this study.

The following sections detail the equipment and methods used to investigate the dynamic properties of the Port Inland limestone. Testing was conducted using a 60-foot long three-inch diameter Split Hopkinson Pressure Bar (SHPB) located on Michigan Tech's campus.

3.4.2 Experimental Procedure

3.4.2.1 Sample Collection and Preparation

Samples of rock were obtained from the Port Inland Quarry in the fall of 2013. The rock samples were cored using a clutch driven coring machine and a 1 5/8 inch diamond coring bit while the sample was held on the coring machine base with wood blocks and clamps as shown in Figure 4(a) and (b). Samples were prepared for a length-to-diameter ratio of 2:1 with a cored diameter of 1.85 inches and cut to a length of approximately 3.75 inches. The samples were surface

ground to produce parallel and flat surfaces (Figure 5). Seven samples of Port Inland Limestone that met the 2:1 criteria were used for the high-strain-rate testing and four for static compression testing. A V-Meter was used to determine the sonic velocity of the Port Inland Limestone. This value of 162,000 in/s (4,100 m/sec) was used to calibrate the Split Hopkinson Pressure Bar.

(a) **(b)**

Figure 4 (a) Coring machine and (b) a block of Port Inland Limestone cored.

(a)

(b)

Figure 5 (a) Surface grinding machine and (b) caliper used to measure parallelism of test samples.

3.4.2.2 High-Strain Rate Testing (Split Hopkinson Pressure Bar)

The high strain rate tests were conducted using a three-inch diameter Split Hopkinson Pressure Bar (SHPB) located in the Benedict Laboratory at Michigan Tech. A digital oscilloscope was

used to collect the data. The SHPB system is shown in Figure 6. The test procedures and data analysis used in this study are discussed in Gilbertson (2011).

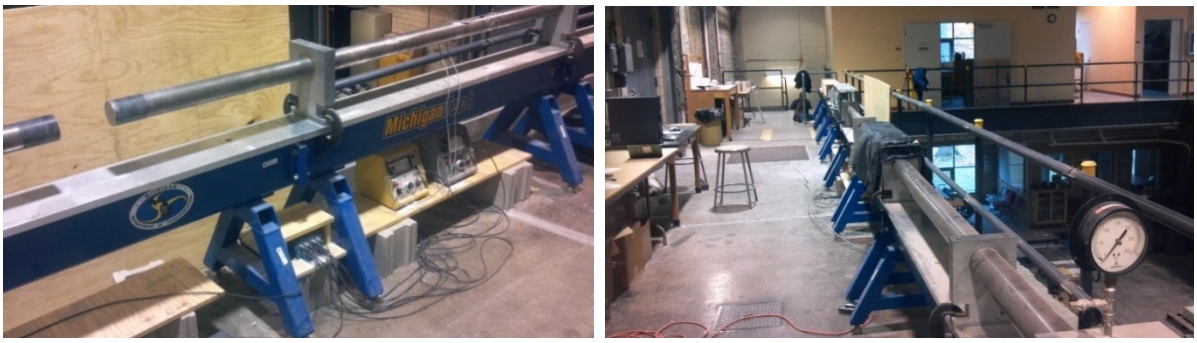


Figure 6 Slip Hopkinson Pressure Bar.

3.4.2.3 Unconfined Compression Strength Testing (UCS)

Unconfined compressive strength testing was conducted using core samples prepared in the same manner as those for SHPB testing. Testing was conducted using a 55 Kip MTS servo-hydraulic testing system located in the Benedict Lab at Michigan tech. The testing procedure followed ASTM C39 using an incremental load rate of 93 pounds per second.

Figure 7: Uniaxial compression testing.

4. Results and Discussion

4.1 Assessment of Michigan Aggregate Quarries to Meet High Speed Rail Ballast

4.1.1 Summary of Existing LAA Specifications

The LAA test was selected as the main parameter for assessing aggregates for this study. A summary of the LAA specifications discussed in this study are summarized in Table 7.

Table 7 Summary of Los Angeles Abrasion (LAA) specifications.

Agency/Country	LAA Specification, Percent	LAA HSR Specification, Percent
MDOT	40	–
AREMA		
Granite	35	–
Traprock (basalt)	25	–
Quartzite	30	–
Limestone	30	–
Dolomite	30	–
Dolomite/Limestone	30	–
Blast Furnace Slag	40	–
Steel Furnace Slag	30	–
Amtrak	18	–
Union Pacific	25	–
European Union	24	–
France	24	17

MDOT has the highest LAA of any of the agencies and countries examined with a LAA of 40%. The only exception is the AREMA specifications that allow a maximum 40% for blast furnace slag. Amtrak had the lowest LAA specification at 18%, a significant difference from the MDOT LAA specification, while the Union Pacific had an LAA of 25%.

4.1.2 MDOT Aggregate Inventory Database

The MDOT aggregate inventory provides LAA values for each operation that have operated in the state producing aggregates for MDOT projects requiring LAA assessment. Since the test is generally conducted at least once every five year period, it has collected a large amount of tests for aggregate operations in Michigan and surrounding states and Canada. For a number of deposits such as carbonates, the LAA values can vary due to natural variability within the formation or possibly mining different formations within the quarry. The database therefore lists both a maximum LAA value that has been recorded for an operation and a minimum LAA as well as the most recent LAA value. As noted above, the data base lists LAA values for the following six deposit types: (1) Blast Furnace Slag (BFSLAG),

(2) Crushed Concrete (CRSH CONC), (3) Igneous and Metamorphic (IG/MET), (4) Quarry, (5) Sand & Gravel (SD/GR) and (6) Steel Furnace Slag (SFSLAG). Quarry deposits are generally carbonate deposits. Since it is unlikely that ballast would be produced at a sand & gravel operation due to the difficulty in generating the larger size particles, it was not considered in this analysis. Steel furnace slag was also not considered leaving the following deposits: (1) BFSLAG, Crushed Concrete, IG/MET and Quarry. The database also includes deposits from nearby states as well as Canada. The average LAA value was determine for each deposit for both the maximum LAA (Max LAA) value and the minimum LAA value (Min LAA) as well as one standard deviation from the mean assuming the data follows an approximate normal distribution. The values are provided in Table 8 for all of the deposits listed in the database and Table 9 for only the deposit in Michigan. The maximum and minimum LAA for each deposit is also provided along with the number of tests values.

A number of observations can be made concerning the results reported in Tables 9 and 10. First, there is not a significant difference between the results from the entire database and the results only for the Michigan deposits.

Second, the "*latest*" LAA test values have been obtained for each quarry is also reported in the MDOT database. Table 10 list the average LAA maximum, LAA minimum, and LAA latest values for each deposit type, rearranged by highest quality(LAA minimum value) to the lowest quality (LAA maximum value). As expected the igneous/metamorphic deposits have the highest quality (19.3%), followed by quarry (carbonate) (30.0%), crushed concrete (30.6%), and finally blast furnace slag (36.5%).

Third, the LAA is considered to be an index test with significant variability. The data reveals, however, the variability of the IG/Met and Crushed Concrete is relatively low compared to the Quarry and BFSLAG deposits when considering the average and standard deviation of the data. This is clearly apparent in Tables 9 and 10. Interestingly, the standard deviation for "Crushed Concrete" has the lowest variability. This should be expected since the material is generally produced from existing concrete roadways that had similar concrete design mixes.

And finally, when considering the MDOT LAA specification of maximum of 40%, it is clear that the most IG/MET and crushed concrete deposits would be able to meet the MDOT LAA specification, while the Quarry and blast furnace slag would have a much lower probability of meeting the LAA specification.

Table 8 LAA values for various deposit types for the entire MDOT aggregate inventory database.

	Blast Furnace Slag		Crushed Concrete		Igneous/Metamorphic		Quarry /Carbonate	
	Max LAA	Min LAA	Max LAA	Min LAA	Max LAA	Min LAA	Max LAA	Min LAA
Database Average	43.9	34.1	31.8	29.3	21.6	18.0	35.2	27.1
Standard Deviation	8.3	10.7	4.6	4.0	6.6	5.5	13.9	13.1
Maximum LAA	53	53	45	42	36	33	97	95
Minimum LAA	24	16	13	13	10	9	12	10
Number of Values	13		134		72		148	

Table 9 LAA values only Michigan aggregate listed in the MDOT aggregate inventory database.

	Blast Furnace Slag	Crushed Concrete	Igneous/Metamorphic	Quarry /Carbonate

	Max LAA	Min LAA	Max LAA	Min LAA	Max LAA	Min LAA	Max LAA	Min LAA
Average	43.8	28.0	31.7	29.3	22.5	18.7	38.0	29.3
Standard Deviation	13.4	17.0	4.6	4.0	6.4	5.4	15.4	15.2
Maximum LAA	53	53	45	42	36	33	97	95
Minimum LAA	24	16	13	13	11	10	14	10
Number of Values	4		132		59		95	

Table 10 Average long term LAA maximum, LAA minimum and the latest LAA value by deposit.

	Igneous/ Metamorphic	Crushed Concrete	Quarry/ Carbonate	Blast Furnace Slag
Database LAA Max Average	21.6	35.2	49.1	52.2
Database LAA Min Average	18.0	27.1	14.0	23.4
Latest LAA Average Values	19.3	30.0	35.1	37.0

4.1.3 Potential Ballast Resources for High Speed Rail

As discussed above, the study found no national ballast standards for HSP. The only HSR standard identified in this study was from France a maximum LAA value of 17%. This value is close to the Amtrak value of 18%. While there are no MDOT HSR specifications, it was assumed for this study that the Amtrak specification of 18% could be used as a likely HSR ballast specification given that passenger service would be operated by Amtrak. Therefore, this study used a LAA value of 18% for assessing aggregate sources for HSR.

To investigate the MDOT inventory for Quarry (Carbonate) and IG/MET deposits the LLA values are plotted in Figures 8 and 9 respectively. It can be seen that for the Quarry (Carbonate) deposits that about 70% of these deposits would consistently be able to meet the MDOT LAA specification of 40%. This is based on the LAA Max being below 40%. Only three carbonate quarries could potentially meet the stricter 18% maximum. All three of these quarries, however, are located in the UP. A fourth quarry, located in Indiana, had a LAA value of 19% which possibly be considered a potential ballast source but this was only for one test. The best carbonate quarry was the Lindberg pit in Marquette county that mines that Kona Dolomite, which had a LAA Max = 14 and a LAA Min =10. This quarry, while still in operation, was last tested in 1958. The Kona Dolomite, however, is a metamorphosed dolomite and therefore should have been listed with the IG/MET quarries. The second quarry with a LAA = 18% (pit 21-96) is located in Delta County was listed in MDOT's EXCEL file but was not listed in the MDOT aggregate inventory database available on the web site so it's unclear if this source is still available. Consequently, there are no carbonate quarries listed in the MDOT inventory database that could consistently meet the 18% LAA value.

An assessment was also made of LAA values for carbonate quarries located in counties that the Michigan Line runs through and the counties adjacent these counties. A total of 14 counties were investigated. The results are provided in Figure 10. Eight quarries were identified that could meet the LLA = 40% specification out of 19 quarries, although as noted above none could meet the 18% specification.

One the other hand all of the IG/MET deposits listed in the MDOT inventory could meet the MDOT specification of 40%, while about 25% would be able to consistently meet a stricter LAA = 18% specification. All of these quarries, however, are located in either the UP or in Canada.

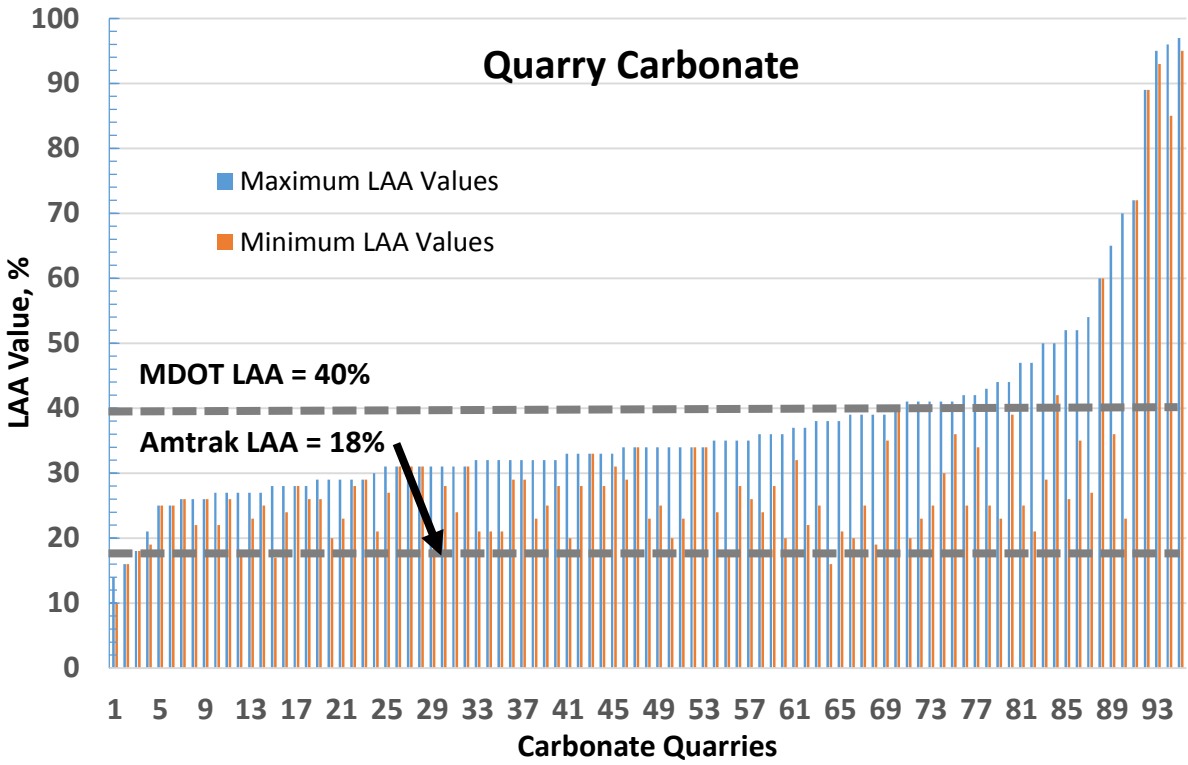


Figure 8 LAA values for crushed concrete.

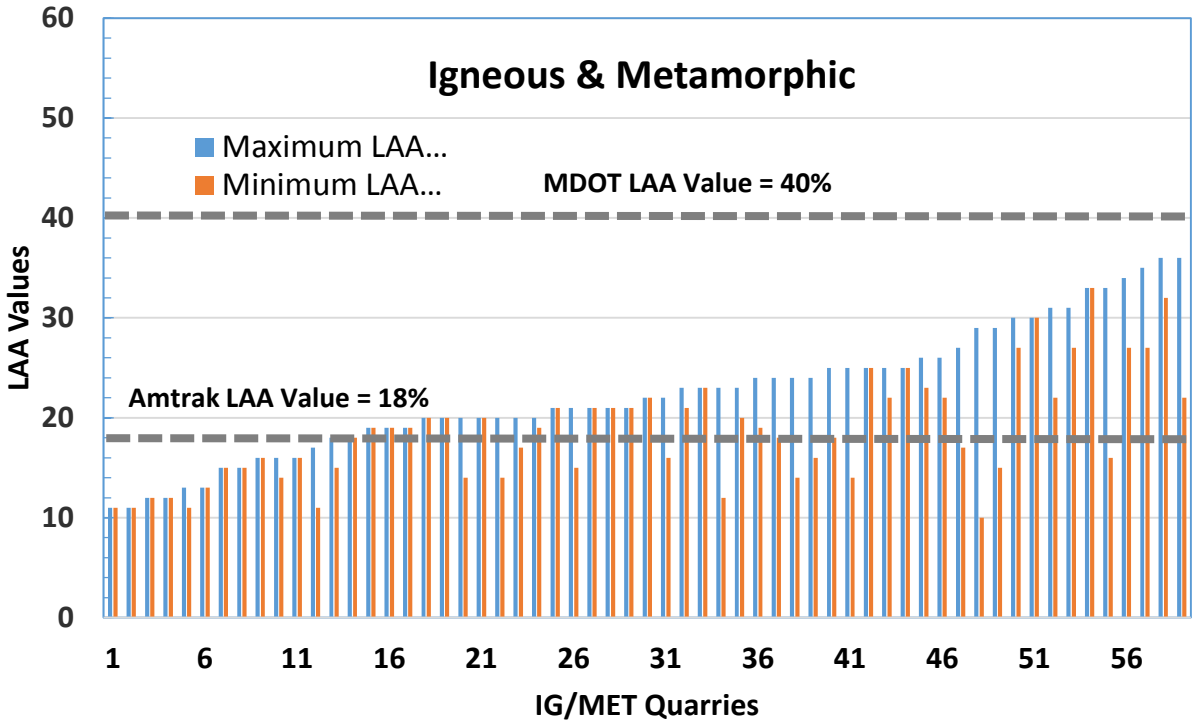


Figure 9 LAA values for igneous & metamorphic deposits.

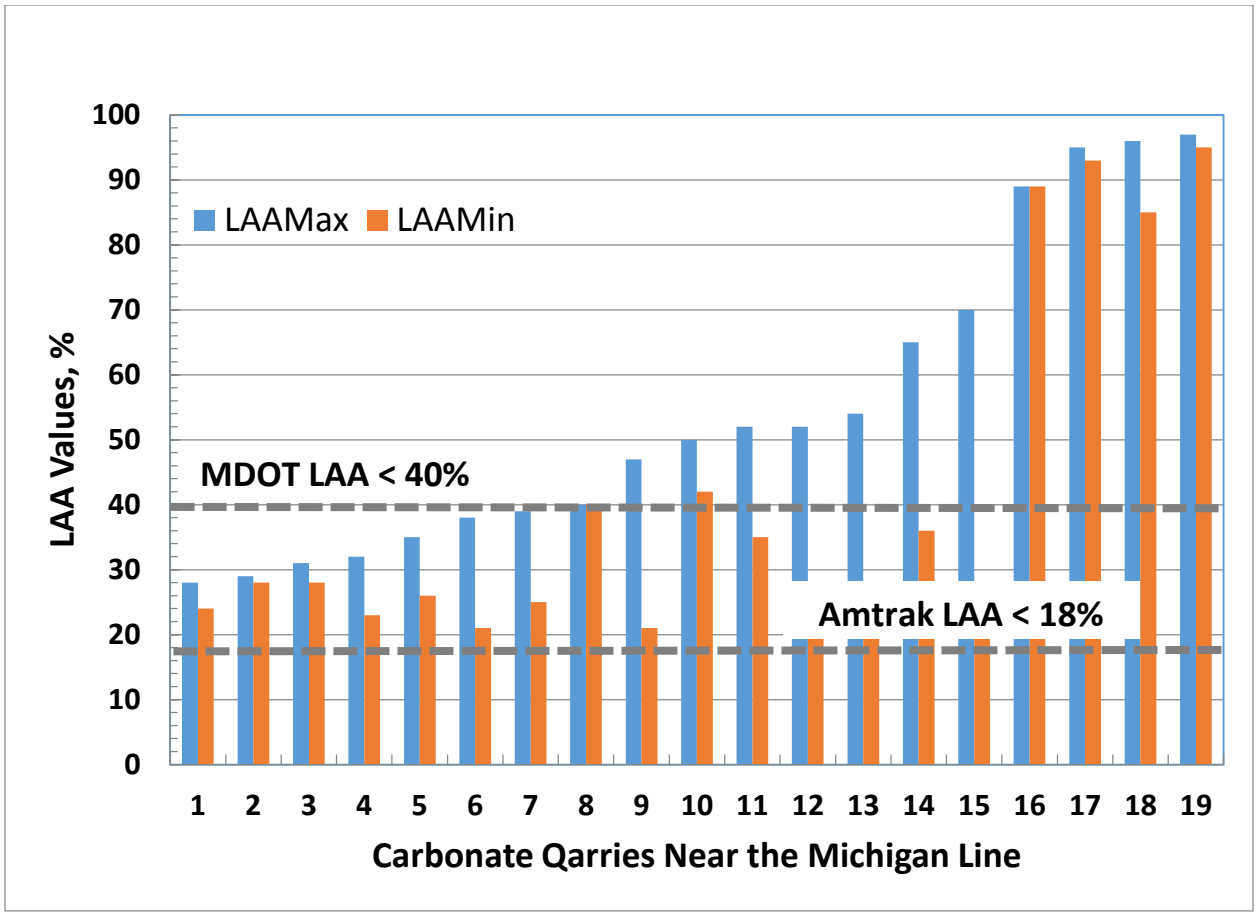


Figure 10 Carbonate quarries located near the Michigan Line.

4.2 Assessment of Iron Mine Waste Rock Piles in the Upper Peninsula

The iron ore mine waste rock piles in the UP are extensive and hold a significant amount of hard, strong metamorphic rock. The waste rock varies in particle size from fines to large boulder. Thus, the waste rock would not require drilling and blasting but would require crushing to meet rail road ballast gradation requirements. Uniaxial compression testing on the waste rock indicated that the rock's strength average between 30,000 and 40,000 psi with the waste rock strength reaching as high as 80,000 psi (Vitton 1978). While the waste rock would obviously make an excellent ballast material, the waste rock piles do have some minor environmental issues. The Cliff Natural Resources (Cliffs) operations near Ishpeming indicate some elevated levels of selenium and lithium. In addition, due to the scale of Cliff's mining operation, the ability to produce smaller amounts of ballast material is limited. As a consequence, Cliffs has not proceeded to market its waste rock piles for commercial use at this time.

Another deposit investigated was the waste rock from the Groveland Mine in northern Dickenson County. The aggregate from this operation was tested in 1986 by the U.S. Corps of Engineers to supply armor stone for its Great Lakes operations. The certification report is provided in Appendix C. This deposit is not included in the MDOT aggregate inventory.

The Groveland Mine aggregate consists of a hard magnetite bearing quartzite. The physical properties are provided below.

LAA	10%
Specific Gravity	3.4 to 3.6
Absorption	< 0.1%
Freeze-thaw 35 cycles	1.1%
Wet-Dray Test	None

The Groveland Mine aggregate would have no problem meeting the Amtrak specifications given its low LAA and additional testing for durability for use as an armor stone.

4.3 Assessment of the Dynamic Properties of the Port Inland Quarry Limestone

As noted above no carbonate quarries listed in the MDOT inventory would be able to meet the 18% LAA requirements, therefore the dynamic properties of the Port Inland Quarry were investigated. The MDOT aggregate inventory list the following LAA values and year tested for the Port Inland Quarry:

LAA Maximum = 39 (1934)
LAA Minimum = 19 (2012)
LAA Latest = 27 (2012)

The four samples of Port Inland limestone were tested in traditional static compression while seven samples were tested in dynamic compression. The results are reported in Table 11. The

average compressive strength was 10,500 psi while the dynamic compressive strength was 33,700 psi, a full three times higher. In fact, the dynamic strength of the Port Inland limestone is approximately equal to the static compressive strength of the iron ore and associated waste rock located at the iron mines in the UP.

Table 11: Port Inland Static and Dynamic Compressive Strength Results.

Port Inland Limestone			
Maximum Static Compressive Stress		**Maximum Dynamic Compressive Strength**	
Sample Number	**Stress, psi**	**Sample Number**	**Stress, psi**
1	9,570	**1**	47,600
2	11,600	**2**	36,000
3	15,000	**3**	38,000
4	6,040	**4**	36,000
Average	**10,500**	**5**	34,000
		6	22,000
		7	22,000
		Average	**33,700**

The field of high strain rate testing, especially for rocks, has only recently been investigated. Almost all of the research conducted in this area deals with its application to fragmentation such as with explosives, military applications and more recently to the dynamic behavior of coarse aggregate for PCC pavements. It is likely though, that the dynamic properties of ballast might also be an important indicator of field performance for ballast, especially in the case of carbonates. In reviewing the current research on ballast the following point by Chrismer was cited:

> *Chrismer (1997), in a later research paper, states that current specified laboratory tests for ballast may not be a reliable indicator of actual ballast breakdown because limitations of the tests do not sufficiently duplicate the environment and breakdown mechanisms. A small number of in-service durability tests of ballast materials have shown certain laboratory tests to be better indicators than others at predicting ballast life and performance.*

As discussed, the only criteria used in this study used to assess aggregates for HSR was the LAA test. This test, however, not represent the complete range of dynamic stresses that are imposed on the ballast in the field. In addition, the LAA test is conducted in a dry state. The Micro-Deval, on the other hand, is conducted in a wet state but with much smaller steel balls and thus lower dynamic loadings. In fact the strain rate of both tests when considering the particle-to-particle loading is very low compared to actual field stresses. Consequently, the dynamic testing of aggregate might provide “another” test that could be conducted in both dry and wet conditions at relatively minimum costs. Further research, however, would be needed to support this claim.

5. Conclusions and Recommendations

The following conclusions were determined in this study:

7. The majority of aggregate quarries in the Lower Peninsula and the eastern half of the Upper Peninsula are carbonate quarries. Igneous and metamorphic quarries occur in the western end of the Upper Peninsula and in Canada.

8. In this study, the Los Angeles Abrasion (LAA) test was used to assess aggregates listed in the MDOT aggregate inventory database for use as a source for ballast material. The database also lists other deposit types such as crushed concrete", blast furnace slag, steel slag and sand & gravel deposits. Only the carbonate and igneous and metamorphic deposits were considered in this study.

9. MDOT has seven specifications used to assess railroad ballast. The most significant specification is the LAA value with is a maximum value of 40%. This is a relatively low LAA value and one of the lowest identified in reviewing major US railroad ballast specifications.

10. According to the MDOT aggregate inventory database, however, 70% of carbonate aggregates in Michigan and surrounding states have a LAA values less than 40% and could be used for railroad ballast. The AREMA LA A value for carbonates is 25%, while Amtrak uses a maximum LAA of 18%. None of the carbonate quarries in Michigan and surrounding states could likely meet a lower 18% LAA specification.

11. All of the igneous and metamorphic quarries listed in the MDOT aggregate inventory database could meet the MDOT LAA specification of 40%, while about 25% could consistently meet the stricter Amtrak specification of 18%

12. The static strength of the Port Inland Quarry limestone was measured to be about 10,500 psi, while its dynamic strength was 33,700 psi. While the static strength is comparable to other limestones, the dynamic strength is significantly higher than found for other limestones or dolomites.

The following recommendations are suggested:

1. The MDOT specification of LLA be less than 40% should be reviewed. While economics of the cost, transportation and replacement will be the main factor in determining the ballast type used, the current specification used by major US railroads and internationally all use a much lower LAA specification.

2. The LAA test is not the only test used to assess ballast material. The Micro-deval and the mill tests are to tests that are being used and should also be considered. It is recommended that additional testing be conducted to determine if the dynamic properties of carbonates might indicate that they can be considered for ballast for the Michigan Line HSR.

Bibliography

Arm, M. (2003), “Mechanical Properties of Residues as Unbound Road Materials.” Ph.D. Thesis. The Royal Institute of Technology, Stockholm, Sweden.

ASTM (2008), Annual Book of ASTM Standards, West Conshohocken, Pennsylvania. Browness et al. (2007)

Chrismer, S.M. (1995), “In Service Testing of Railroad Ballast”, International Center for Aggregate Research, 3rd Annual Symposium, Austin, TX.

Chrismer, S.M. and E. Selig, (1994), Mechanics-Based Model to Predict Ballast-Related Maintenance Timing and Costs. Association of American Railroads, Chicago, Illinois, Report No. R-863, July.

Doyle, N. F, (1980), “Railway Track Design a Review of Current Practice, BHP Melbourne Research Laboratories, Australian Government Publishing Service, Camberra, p. 280.

Ernest T. Selig, and D. L. Boucher, (1990), "Abrasion tests for railroad ballast," ASTM Geotechnical Testing Journal, Vol. 13, No. 4, p. 301.

Gilbertson, C, (2011), Dynamic properties of wood using the Split-Hopkinson Pressure Bar, Doctoral Dissertation, Michigan Technological University, Houghton, MI.

Kline, S.W., W. Phiukhao, M.L. Griffin, and J.W. Miller, Evaluation of the sodium sulfate soundness test for qualifying dolomites of northern Arkansas for construction aggregate. In

Shaffer, N.R., and DeChurch, D.A., eds, Proceedings of the 40th Forum on the Geology of Industrial Minerals, 2004: Indiana Geological Survey Occasional Paper 67, 2007.

Li, D., and Selig, E. T., 1998, “Method for railway track foundation design. II: Applications.” J. Geotech. Geoenviron. Eng., 1244, 323–329.

Quinn, A., Hayward, M., Baker, C. J., Schmid, F., Priest, J. A., & Powrie, W. (2010). A full-scale experimental and modelling study of ballast flight under high-speed trains. Journal of Rail and Rapid Transit, 61-74.

Peterman, D. R., J. Frittelli, and W.J. Mallet, 2009, High Speed Rail (HSR) in the United States, Congressional Research Service, US Government, R40973, p.31.

Robnett, Q.L., Thompson, M.R., Hay, W.W., Flayabji, S.D., Peterson, H.C., Knutson, R.M., Baugher, R.W. (1975) Technics% Data 3ases Report, Ballast and Foundation Materials Research Program, FRA Report No. FRA-OR&D-76-138, National Technical Information Service, Springfield, Virginia, USA.

Rogers, C.A., Bailey, M.L. and Price, B. (1991). “Micro-Deval Test for Evaluating the Quality of Fine Aggregate for Concrete and Asphalt.” Transportation Research Record 1301.

Rogers, C., Canadian Experience with the Micro-Deval Test for Aggregates. In: Latham, J.P. (ed.) 1998. Advances in Aggregates and Armourstone Evaluation. Geological Society, London, Engineering Geology Special Publications, 13, 139-147.

Talbot, A.N. (1919) Stresses in Railroad Track. The Second Progress Report of the ASCE-AREA Special Committee on Stresses in Railroad Track, Reprinted, 1980. Published by the American Railway Engineering Association (AREA).

Vitton, S.J. (1978), “The Effects of Cold Temperatures on the Properties of Iron Ore”, MS Thesis, Michigan Technological University, Houghton, MI.

Vitton, S.J., (2002), Mechanical Testing of Rock Cores Test Hole TH-7 MDOT Structure B02 of 22023 J.N. 51442A US-2 Over Sturgeon River Dickenson County, Michigan, Michigan Department of Transportation, Job Number 96-5434, p. 18.

Vitton, S.J., (2008), Location and Stability Analysis of the Michigamme Underground Mine for the US-41 Re-Alignment in Marquette County, Michigan, Michigan Department of Transportation, RC-1510, p. 36.

Vitton, S.J., Subash, G. and Dewey, G. (2002), “Evaluation of the Dynamic Fracture Characteristics of Aggregate in PCC Concrete, MDOT, RC-1415, Lansing, MI, p.493.

Abbreviations and Acronyms

A_N	Abrasion Number
AREMA	American Railway Engineering and Maintenance-of-Way Association
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
AWI	Aggregate Wear Index
BFSLAG	Blast Furnace Slag
CLIFFS	Cliff Natural Resources
CRSH CONC	Crushed Concrete
EAC	Equivalent Annual Costs
FRA	Federal Railroad Administration
HSR	High Speed Rail
IG/MET	Igneous and Metamorphic
LAA	Los Angeles Abrasion
MDE	Micro-deval Test
MDOT	Michigan Department of Transportation
MGT	Million Gross Tons
NS	Norfolk and Southern
SD/GR	Sand & Gravel
SFSLAG	Steel Furnace Slag
SHPB	Split Hopkinson Pressure Bar
UCS	Unconfined Compression Strength Testing

Appendix A

MDOT Standard Specifications for Railroad Work 2006

DIVISION 3

BALLAST

Section 30. BALLAST AND SUB-BALLAST

30.01 Description. This work consists of furnishing and placing ballast or sub-ballast at specified locations and rates as may be amended by the Engineer/FDI.

30.02 Materials. The materials shall meet the following specifications:

Ballast .....Section 91.

Sub-ballast..... Section 92.

30.03 Construction. The subgrade shall be prepared according to Subsection 205.03.F of the Standard Specifications for Construction. Sub-ballast shall be laid in layers not greater than 6"deep. Water shall be added to facilitate compaction when material is too dry. Rolling may be by pneumatic-tired equipment heavily loaded or by vibratory roller. Small vibrator or pneumatic tampers shall be used where larger rollers cannot work. All compaction shall be uniformly distributed so all layers are compacted to 95 percent density by control density method.

Ballast shall be distributed using a 3/4 ton (minimum) come-along to achieve the rates specified. Additional lengths of 3/8" chains shall be available and used where necessary to control the distribution rate. The method of distribution shall be approved by the Engineer/FDI prior to unloading. Ballast shall be placed on mainline track and yards by work train, except at grade crossings and point specific locations where a hi-rail dump truck may be used.

Each delivered load shall be accurately weighed and accompanied by a certified scale ticket showing gross, tare, and net weights. This requirement may be waived by the Engineer/FDI when scales are not readily accessible. In that case, a unit train would be run over a scale and the average unit weight per car would be the base. Weights shall be recorded to the nearest 100 pounds. Scales shall comply with Subsection 109.01.G of the Standard Specifications for Construction when loads are delivered by truck. Railroad car scales shall meet the requirements of Section 1.0 of the current AAR Scale Handbook. The Contractor shall provide documentation to prove that all AAR requirements are met.

30.04 Inspection. If the Department elects to inspect ballast at the point of production, its representatives shall have access to the plants and quarries while ballast is being prepared or loaded from storage piles. The material shall be placed into stockpiles and removed from stockpiles by methods that provide aggregate of uniform grading. If inspection reveals that material loaded or stockpiled does not conform to these specifications, the producer will be so notified and production stopped.

Ballast shall meet specifications in its final resting place. The Contractor will be responsible for removal of all material that fails to meet specifications.

30.05 Measurement and Payment.

Contract Item (Pay Item) Pay Unit

Ballast, Sub..... Cubic Yard

Ballast #__..... Ton

Ballast, Sub will be measured for each cubic yard of sub-ballast compacted in place.

Ballast #__ (4A, 4, 5) will be measured for each ton of ballast placed. Payment includes producing, delivering, and distributing the ballast.

Section 91. BALLAST

91.01 General Requirements. The Contractor shall arrange for all ballast testing. Ballast shall be tested by or under the direct supervision of a Certified Aggregate Technician. Prior to placing the ballast, the Contractor shall provide the Engineer/FDI with certified test results showing conformance with the specification requirements.

91.02 Testing Requirements. Ballast shall be 100 percent crushed material prepared from stone or steel furnace slag (SF slag) and composed of hard, strong, and durable particles, free from excess deleterious substances. The processed material shall have an angular structure with all faces fractured, providing sharp corners with a minimum of flat and elongated pieces. Ballast shall meet the following requirements:

A. Grading – Gradation testing shall be performed using ASTM Test Method C136. Crushed stone and crushed slag for processed ballast shall conform to these grading requirements for the Size Number specified in the plans/proposal.

Amount Finer Than Each Sieve
Percent by Weight

Size No.	Nominal Size (inch)	2½"	2"	1½"	1"	3/4"	½"	3/8"	#4
4A	50 – 19 100	90-100	60-90	10-35	0-10	--	0-3	-	
4	38 – 19 --	100	90-100		20-55	0-15	--	0-5	-
5	25 - 9.5 --	100	100		90-100	40-75	15-35	0-15	0-5

B. Soft Particles – Deleterious particle testing shall be performed using Michigan Test Method 110. Soft particles include: shale, siltstone, friable sandstone, ochre, coal, and particles that are structurally weak (particles can be broken or crumbled by the fingers of one hand). Soft particles shall not exceed 5 percent.

C. Loss by Washing – Loss by wash testing shall be performed using ASTM Test Method C117, Procedure A. Loss by washing shall not exceed 2 percent.

D. Abrasion Resistance – Abrasion resistance testing shall be performed using ASTM Test Method C131. Prepared ballast shall have a loss not greater than 40 percent.

E. Soundness – Soundness testing shall be performed according to ASTM Test Method C88, using either magnesium sulfate or sodium sulfate. When subjected to five cycles of the soundness test, the ballast

shall have a weighed loss of not more than 12 percent when sodium sulfate is used or not more than 18 percent when magnesium sulfate is used.

Procedure A of AASHTO T103 - 9I is also an acceptable method for testing ballast for soundness. When performing the AASHTO T103 - 9I test, the sample shall be completely frozen at a temperature not higher than -15$_o$F, and completely thawed to constitute a cycle. The duration of the freezing and thawing periods shall be reported along with the test results. Prepared ballast, when subjected to 50 freeze/thaw cycles using the AASHTO T103 - 9I test, shall have a weight loss of not more than 5% on any screen.

F. Unit Weight – Unit weight testing shall be performed using ASTM Test Method C29,

Rodding Procedure, using the ballast grade specified.

G. Flat or Elongated Particles – Particle testing shall be performed using ASTM Test Method D4791, using a ratio of 5:1 to determine flat or elongated particles. The portion of the prepared ballast retained on the 3/8" sieve shall not contain more than five percent flat or elongated particles, or both.

91.03 Testing Frequency. Testing shall be done at a minimum frequency of one test per 5,000 tons of ballast furnished for gradation, loss by washing, soft particles, unit weight, and flat or elongated particles. Abrasion resistance and soundness shall be tested at least once per project per source. Additional tests shall be performed, if the character of the aggregate changes. The Engineer/FDI may require additional testing or may collect samples for testing to confirm certification results. The Engineer/FDI has the discretion to visually inspect the ballast where, in the opinion of the Engineer/FDI, the quantities involved do not warrant formal testing procedures.

91.04 Production and Handling. When crushed stone or crushed slag does not become clean without washing, a suitable arrangement shall be provided at the quarry or crusher for that purpose. Crushed stone and slag for ballast shall be handled in such a manner that is kept clean and free from dirt and debris.

Section 92. SUB-BALLAST

92.01 Requirements. Materials intended for use as sub-ballast shall conform to current ASTM designation D 1241 for quality and MDOT Michigan series 22A for size requirements, as per Section 902.06 of the Standard Specifications.

Appendix B

British Railway Ballast Standards

BS EN13450:2002

Tables from:

Aggregates for railway ballast

Table 1 — Categories for grading

Sieve size mm	Railway ballast size 31,5 mm to 50 mm			Railway ballast size 31,5 mm to 63 mm		
	Percentage passing by mass					
	Grading category					
	A	B	C	D	E	F
80	100	100	100	100	100	100
63	100	97 to 100	95 to 100	97 to 99	95 to 99	93 to 99
50	70 to 99	70 to 99	70 to 99	65 to 99	55 to 99	45 to 70
40	30 to 65	30 to 70	25 to 75	30 to 65	25 to 75	15 to 40
31,5	1 to 25	1 to 25	1 to 25	1 to 25	1 to 25	0 to 7
22,4	0 to 3	0 to 3	0 to 3	0 to 3	0 to 3	0 to 7
31,5 to 50	≥ 50	≥ 50	≥ 50	-	-	-
31,5 to 63	-	-	-	≥ 50	≥ 50	≥ 85

NOTE 1 The requirement for passing the 22,4 mm sieve applies to railway ballast sampled at the place of production.

NOTE 2 In certain circumstances a 25 mm sieve may be used as an alternative to the 22,4 mm sieve when a tolerance of 0 to 5 would apply (0 to 7 for category F).

Table 2 — Categories for fine particles content

Sieve size mm	Maximum percentage passing by mass			
	Fine particle category			
	A	B	Declared	C
0,5	0,6	1,0	> 1,0	No requirement

NOTE The requirement applies to railway ballast sampled at the place of production.

Table 3 — Categories for fines content

Sieve size mm	Maximum percentage passing by mass				
	Fines content category				
	A	B	C	Declared	D
0,063	0,5	1,0	1,5	> 1,5	No requirement

NOTE The requirement applies to railway ballast sampled at the place of production.

Table 4 — Categories for maximum values of flakiness index

Flakiness Index	Category *FI*
≤ 15	FI_{15}
≤ 20	FI_{20}
≤ 35	FI_{35}
> 35	$FI_{Declared}$
No requirement	FI_{NR}

Table 5 — Categories for maximum values of shape index

Shape Index	Category *SI*
≤ 10	SI_{10}
≤ 20	SI_{20}
≤ 30	SI_{30}
5 to 30	$SI_{5/30}$
> 30	$SI_{Declared}$
No requirement	SI_{NR}

Table 6 — Categories for particle length

Percentage by mass with length ≥ 100 mm in a greater than 40 kg sample					
Particle length category					
A	B	C	D	Declared	E
4	6	8	12	> 12	No requirement

Table 7 — Categories for maximum values of Los Angeles coefficient

Los Angeles coefficient	Category LA_{RB}
≤ 12	LA_{RB} 12
≤ 14	LA_{RB} 14
≤ 16	LA_{RB} 16
≤ 20	LA_{RB} 20
≤ 24	LA_{RB} 24
> 24	LA_{RB} Declared
No requirement	LA_{RB} NR

Table 8 — Categories for maximum values of resistance to impact

Impact value %	Category SZ_{RB}
≤ 14	SZ_{RB} 14
≤ 18	SZ_{RB} 18
≤ 22	SZ_{RB} 22
> 22	SZ_{RB} Declared
No requirement	SZ_{RB} NR

Table 9 — Categories for maximum values of resistance to wear

micro-Deval coefficient	Category M_{DE} RB
≤ 5	M_{DE} RB 5
≤ 7	M_{DE} RB 7
≤ 11	M_{DE} RB 11
≤ 15	M_{DE} RB 15
> 15	M_{DE} RB Declared
No requirement	M_{DE} RB NR

Appendix C

Cloverland Iron Mine Waste Rock Aggregate U.S. Corps of Engineer's Report

Reports Control Symbol - CYDVT-3

PETROGRAPHIC REPORT outside of Iron Mt.	Corps of Engineers U.S. Army OHIO RIVER DIVISION LABORATORIES Mariemont, Ohio 45227	
Source: Groveland Mine Dump, Randville, Michigan		Date: July 1986
Material: Armorstone - 400 lbs.		Lab Sample No.: G-1 & G-2
Project: Keweenaw Waterway	District: Detroit	Lab Job No.: 103/86.622D

SUMMARY

Sample G-1 was found to consist of a distinctly layered Magnetite-bearing Quartzite. Sample G-2 was also found to consist of a Magnetite-bearing Quartzite but only crude layering is present.

INTRODUCTION

Two samples of stone, weighing approximately 400 lb. each from the Groveland Mine Dump, Randville, Michigan, were submitted to ORDL by the Detroit District for examination and testing. The samples are purportedly representative of material being considered for use as armorstone for the Keweenaw Waterway Project.

DISCUSSION

Each sample was examined as received. After sawing, representative portions of each sample were examined megascopically and with a stereomicroscope. The samples were both found to consist of Magnetite-bearing Quartzite, as described in detail below.

CONCLUSIONS

Based on the results of laboratory testing, material of which both samples are representative appears to be suitable for the intended use.

Terry Stransky
Geologist

ORD 1 Form 22 Jan 68 608 Previous edition may be used Lab

G-1 MAGNETITE-BEARING QUARTZITE - Reddish-brown to medium dark gray, fine grained, distinctly layered. Layering is wavy and often discontinuous, especially the reddish-brown layers.

The sample consists of a well-cemented quartzite with variable amounts of interstitial magnetite. Nearly pure magnetite layers of variable thickness and higher crystallinity are present. Partial, localized oxidation of the magnetite to hematite, and later deformation has resulted in a number of sausage-shaped boudinage structures (boudins) containing a core of pure magnetite or magnetite-bearing quartzite surrounded by a rind of bright orange to orange-red hematite. These boudins vary greatly in size and thickness; the largest is 1/4" thick X 1 foot long (the thickest observed boudin is approximately 3/4" thick).

The sample exhibits several episodes of deformation. The earlier occurring episode, which took place in the plastic state, involved the development of the elongated, sausage-like hematitic boudins described above. A second deformation episode involved the development of normal microfaulting, resulting in the localized offset of many layers by as much as 1/2" - 3/4". These microfaults are generally at a very high angle to the bedding (75-90 degrees) and continuous throughout the thickness of the sample. A second series of short (less than 1") fractures cutting only individual boudins has the same orientation as the larger set, but no displacement is noted: crystalline magnetite generally fills these fractures.

A third, and apparently the latest, deformation episode has resulted in several widely spaced, continuous, partially open, slightly weathered fractures oriented approximately 60 degrees to the bedding. While these fractures are partly open, and the sample tends to part along them, little or no adverse reaction to accelerated weathering tests was noted.

The sample is very hard, very tough, dense, with a blocky fracture.

G-2 MAGNETITE-BEARING QUARTZITE - Light gray to medium dark gray and reddish-brown, highly mottled, very crudely and irregularly layered, fine grained. Fresh faces show the frosty look typical of quartzite.

The sample consists of quartzite containing highly variable amounts of interstitial magnetite, and, where locally oxidized, hematite. Concentrations of magnetite vary considerably throughout the sample, from nearly pure magnetite zones to pure quartzite zones. Layering is due to variable concentrations of granular and occasional poorly crystalline magnetite, within the quartzite. Occasionally, the magnetite occurs as thin, wavy, often discontinuous seams 1/16"-1/8" thick and several inches long.

The sample contains a single continuous open fracture subparallel to the bedding. This fracture contains a discontinuous film of white calcite, is weak, and the sample parts readily along it. No other fracturing or planes of weakness are present in the sample.

The sample is very hard, very tough and dense with a blocky fracture.

ACCELERATED WEATHERING TESTING PROCEDURES

FREEZE-THAW TEST

This accelerated weathering test simulates the type of exposure to which the rock specimens would be subjected under winter-time conditions and is used to determine the weathering characteristics of the rock under these conditions.

The test consists of soaking 2½" thick slabs cut (normal to bedding) from the rock specimens in a 0.5% alcohol-water solution for twelve hours followed by freezing the slabs immersed in the liquid at -25°F (-32°C) for twelve hours and then thawing at +90°F (+32°C) for twelve hours. One cycle consists of twelve hours freezing followed by twelve hours thawing.

The alcohol-water solution must be replenished, generally, every three to four days.

The specimens are oven-dried at 200°F for 24 hours and weighed to the nearest gram before and after testing. Loss due to freeze-thaw may then be determined by the following formula:

$$\% \text{ loss} = \frac{A-B}{A} \times 100$$

where,

A = oven-dried weight of specimen before test.
B = oven-dried weight of largest remaining piece after the test.

"Before" and "after" photographs are taken of each specimen and the condition of each specimen, as to the presence of fractures, is also noted before and after testing.

WET-DRY TEST

This accelerated weathering test is designed to simulate summer-time conditions of alternating rainfall and subsequent drying by the summer sun. This test is used to determine the weathering characteristics of rock in a summer-type environment.

The test consists of soaking 2½" thick slabs cut (normal to bedding) from the specimens in water at 50°F (10°C) for six hours followed by drying under infra-red heat lamps for six hours.

The infra-red lamps produce a surface temperature of about 140°F (60°C) for medium-colored rocks (cooler for light-colored rocks and warmer for dark-colored rocks). Each period of soaking and drying is one cycle.

The specimens are oven-dried at 200°F for 24 hours and then weighed, both before and after testing in order that any loss due to wetting and drying can be determined as it is for the freeze-thaw test. Also like the freeze-thaw test, "before" and "after" photos are taken and the condition of the specimen is noted before and after [illegible]

PHYSICAL TEST RESULTS

Source: Groveland Mine Dump, Randville, Michigan

Material: Armorstone - 400 lbs.

Specimen: G-1

1. Specific Gravity (Average of 2 tests): 3.622
2. Absorption (24 hours) (Average of 2 tests): 0.115%
3. Accelerated Weathering Tests:

   a. Wet-Dry

      Number of Cycles: 80

      Percent of Loss: 0.0

      Effects Description: None

   b. Freeze-Thaw

      Number of Cycles: 35

      Percent of Loss: 1.134

      Effects Description: Slight loss due to parting along bedding, at corner of sample.

26

PHYSICAL TEST RESULTS

Source: Groveland Mine Dump, Randville, Michigan

Material: Armorstone - 400 lbs.

Specimen: G-2

1. Specific Gravity (Average of 2 tests): 3.400
2. Absorption (24 hours) (Average of 2 tests): 0.107%
3. Accelerated Weathering Tests:

   a. Wet-Dry

      Number of Cycles: 80

      Percent of Loss: 0.0

      Effects Description: None

   b. Freeze-Thaw

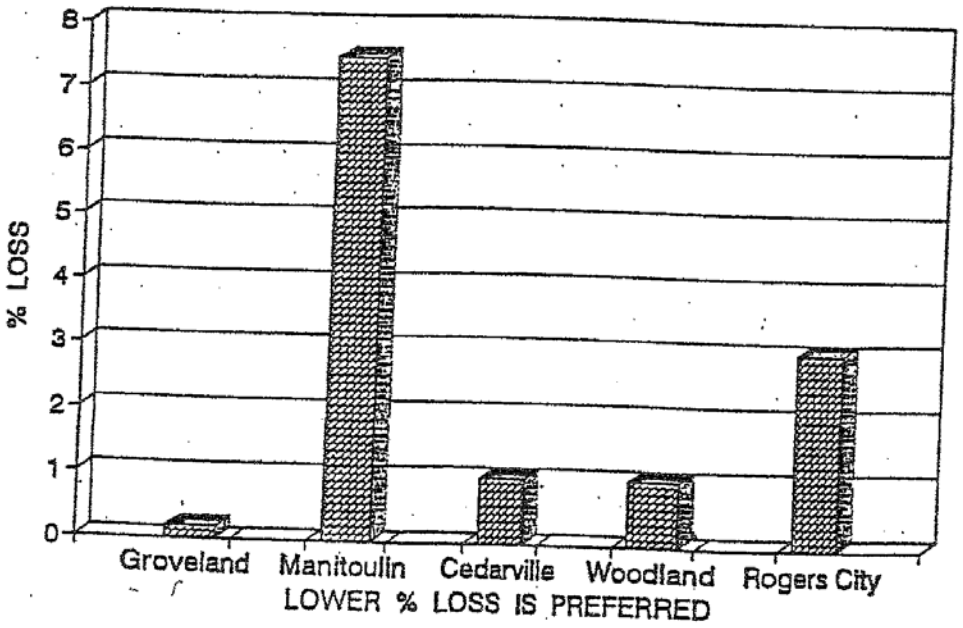
      Number of Cycles: 35

      Percent of Loss: 0.0

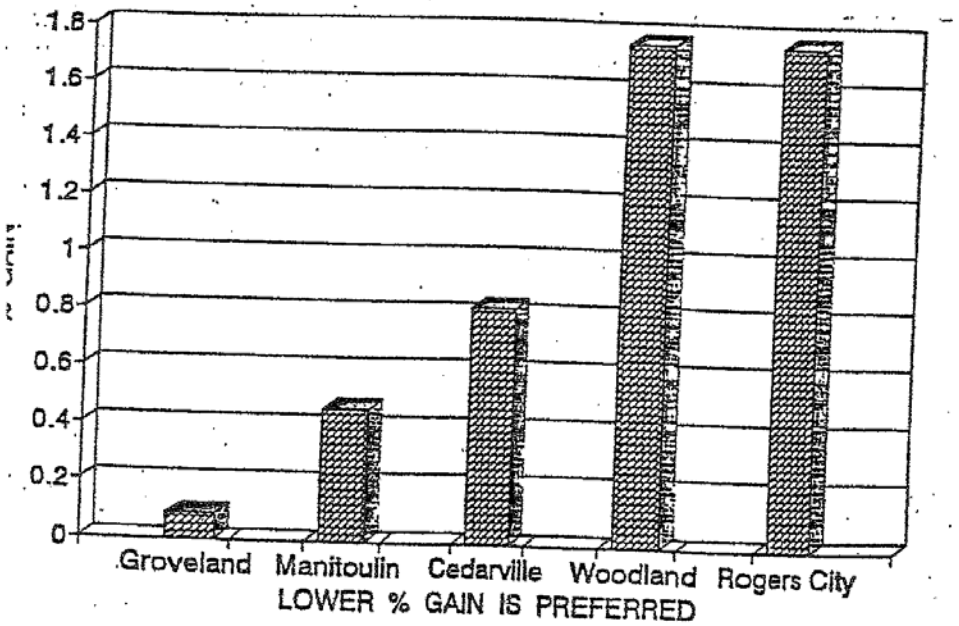
      Effects Description: None

Groveland Mine

SULFATE SOUNDNESS
% LOSS COMPARISON



ABSORPTION INDEX
% GAIN COMPARISON



L. A. ABRASION INDEX
% LOSS COMPARISON