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July 2007 Progress Report
To the Economic Development Administration

Research, Development, and Marketing of Minnesota's Iron Range Aggregate Materials for Midwest and National Transportation Applications

Project # 06-79-05068

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This publication is accessible from the home page of the Economic Geology Group of the Center for Applied Research and Technology Development at the Natural Resources Research Institute, University of Minnesota, Duluth (http://www.nrri.umn.edu/egg) as a PDF file readable with Adobe Acrobat 6.0.

Date of release: July, 2007

Cover Photo Caption

Ulland Brothers, Inc. taconite aggregate production site near U.S. Steel's Minntac operation, Mountain Iron, MN.

Recommended Citation

Zanko, L.M., Fosnacht, D.R., and Hauck, S.A., 2007, Research, Development, and Marketing of Minnesota's Iron Range Aggregate Materials for Midwest and National Transportation Applications: July 2007 Progress Report to the Economic Development Administration, Natural Resources Research Institute, University of Minnesota, Duluth, MN, Technical Summary Report NRRI/TSR-2007/02, 50 pp.

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INTRODUCTION AND BACKGROUND

Every year, Minnesota's taconite mining industry generates over 125 million tons of mining byproducts, a figure that is more than double the entire state's annual aggregate usage. Since 2000, the Natural Resources Research Institute (NRRI), University of Minnesota, Duluth, has been investigating how these vast quantities of taconite mining byproducts can be used for construction aggregate purposes on an expanded basis.

The Economic Development Administration (EDA) is supporting a comprehensive three-year (2006-2008) research and demonstration program. The program's main objectives are to: 1) identify new and economically viable uses for Minnesota Iron Range taconite aggregate material in road construction and repair projects; and 2) conduct demonstration projects inside and outside Minnesota, including several targeted Upper Midwest States. To assure program success, a cooperative and collaborative research approach is being taken, one which involves the staff and facilities of the University of Minnesota in Duluth and the Twin Cities; the Minnesota Department of Transportation (Mn/DOT); Minnesota state agencies and organizations; upper Midwest and Great Lakes state DOTs; the taconite industry; and other public and private sector transportation and aggregate industry professionals, organizations, and individuals.

The program has two major phases. The first phase is aimed at assessing the resource and road construction market opportunity in terms of technical information on aggregate applications, unique properties and benefits, different mix designs and their attributes, alternative products and technologies, and to build awareness and interest in the expanded use of taconite aggregate products at the regional and national scale. Material transportation logistics and costs, and market opportunities and approaches to demonstrate taconite aggregate's advantages will also be assessed during this first phase. The second phase will expand on the first phase findings and use them as a guide for demonstrating the actual use of taconite aggregate products on a larger scale throughout Minnesota and the Midwest in a variety of potential construction applications. Technical work will continue on an expanded basis, as will further investigation and demonstration of innovative products and technologies.

This report summarizes program activities conducted during a period that spans both phases.

Program Funding and Budget: January 1, 2006 to December 31, 2008

Dept. of Commerce – EDA:	$1,250,000
Matching Funds	
NRRI-UMD	175,667
Iron Range Resources	175,000
Minnesota Technology (via NRRI)	46,000
Blandin Foundation	10,000
Minnesota Power	10,000
Total Budget	**$1,666,667**

Contracting

The research program also relies on individuals/groups having expertise in specific project areas. Contracts for professional services are now in place for the initial phase of the research program, and are summarized below.

Contracts for professional services relevant to the January-June 2007 reporting period:

- The Tinklenberg Group: introduction of concept, communications and marketing, logistics, and research

- The Tinklenberg Group has facilitated interaction with USDOT, various state DOTs, contractors, and transportation providers, and collaborated in developing marketing materials for introducing Mesabi Hard Rock™ to potential end-users for demonstration projects. Their contributions to the project are significant, and are detailed via their 2007 reporting (Appendix A).

- Dr. David M. Hopstock and Associates, LLC: microwave applications research
  - Dr. Hopstock and his associate, David Lindroth, provide the conceptual and operational expertise needed to perform the microwave-related research, including the setup and safe use of the 15kW microwave generator at NRRI Duluth.

Sub-award (approved January, 2007)

- Mn/DOT – MnROAD: Support of pavement research activities at the Albertville, MN, facility, including performance monitoring of existing taconite pavements (asphalt and concrete) in the facility's Low Volume Road. Main Line (Interstate 94) installation and monitoring of taconite aggregate pavements is anticipated during the program's second phase.

PROJECT OVERVIEW: January – June, 2007

To recap, the research program's major areas of focus are listed below. ***Program activities have now commenced in all areas.***

- Introduction of Concept
- Preliminary Research
- Sample Acquisition and Preparation
- Aggregate Testing
- Geology, Mineralogy, and Chemistry
- Mix Design
- Innovative Concepts/Uses
  - Pothole patching compounds
  - Microwave heating (pavement conditioning/annealing), pothole patching, and de-icing
- Demonstration Projects
  - MnROAD Field Demonstrations
  - Field Demonstrations
- Transportation Logistics and Economics
- Communications and Marketing

SIGNIFICANT PROGRAM ACTIVITIES

The program's most significant activities between January 1 and June 30, 2007 are highlighted below.

- Collaborated with the University of Minnesota's Department of Civil Engineering and others to submit a proposal to the Federal Highway Administration (FHWA) to host a national Recycled Materials Resource Center (RMRC). Reuse/recycling of taconite mining by-products would have a significant focus in the proposed RMRC. A final proposal was submitted to FHWA the last week of January, 2007. Learned in the springtime that the proposal was not accepted.
- January meeting with Environmental Protection Agency (EPA) Region 5 staff in Chicago, IL, to discuss recycling and reuse issues related to taconite aggregate and dredged harbor sediments.
- Between January and March, continued efforts related to Chicago area demonstration project planned for spring 2007, including working out logistical issues with Illinois DOT (IDOT), the Illinois contractor, the Minnesota contractor, and the shippers. Learned

during a mid-March conference call with IDOT that the highway project in Elgin, IL, where the proposed demonstration was to occur, was postponed due to IDOT budget constraints.

- In February, Ph.D. candidate Ms. Tamara Diedrich joined NRRI's Economic Geology Group. She is working on the development of innovative taconite-based paving materials, and mineralogical and microscopic characterization of taconite aggregates and products.
- April 10 meeting in Hinckley with Transportation and Logistics Working Group, with focus on movement of taconite aggregate via a bi-modal (rail/truck) transportation system, taconite aggregate end uses, and demonstration project candidates in the Twin Cities metro area.
- On April 11, initiated scanning electron microscope (SEM) training at University of Minnesota's Characterization Facility in Minneapolis for the project's ongoing mineralogical work.
- Geological work progressed via the logging of newly-drilled holes at Hibbing Taconite (Hibtac; 2 holes) and at Keewatin Taconite (Keetac; 11 holes), and by using sequence stratigraphy as a tool for looking at small-scale sedimentary features in the drill core to further refine potential depositional environments of the iron-formation. Definition of the environments could be used in the future in attempts to predict lateral changes in horizons with aggregate and iron-ore potential and updated stratigraphic interpretation of potential aggregate units in the Biwabik Iron Formation.
- Provided additional test materials to two private companies interested in producing value-added taconite aggregate-based products (currently under evaluation), and attended a follow-up meeting with one of them to discuss their longer-term plans and material needs.
- Paper presentations were made and Mesabi Hard Rock™ information booths were set up at: 1) 80th Annual Meeting of the SME Minnesota Section and 68th Annual University of Minnesota Mining Symposium in Duluth, MN, in April, 2007; and 2) 43rd Forum on Industrial Minerals in Boulder, CO; in May, 2007.
- Met with United States Geological Survey (USGS) in Denver, CO, to discuss collaborative mineralogical and microscopic testing of taconite aggregate samples and sample testing methodologies.
- Continued bench-scale microwave heat testing of taconite aggregate samples and successful installation and operation of 15kW microwave unit at NRRI in Duluth.
- Long-term (2-year) alkali silica reactivity (ASR) testing of samples by Mn/DOT Office of Materials continued.
- In early and late May, met with another taconite mining company and a contractor that produces taconite aggregates from that mine. Discussions focused on geological control and providing aggregate materials for demonstration projects and testing. Obtained more samples for testing; fifteen 5-gallon buckets were sent to the Illinois Department of Transportation (IDOT) for certification testing; results are pending.
- Finalization of mix design testing plans at University of Minnesota Department of Civil Engineering and initial testing results described.
- Continued working out shipping logistics for planned 2007 large-scale demonstration projects.
- On June 26, attended equipment demonstration of a bi-modal (truck/rail) system that will likely be used for one or more aggregate demonstration projects in late summer or early fall of 2007.

- Prepared final draft report of historical uses of Mesabi Hard Rock™ materials in construction applications in Minnesota. A shortened version of the report will be submitted by the end of July for consideration for presentation at the January, 2008, Transportation Research Board (TRB) meeting in Washington, D.C.

More detailed summaries relevant to the program's major areas of focus are provided on the following pages and/or in the appendices; they include significant contributions from the research program's contractors and participants.

Introduction of Concept

Narrative: The use of aggregate material from the Mesabi Range in not widely known outside of Northeast Minnesota. Baseline work will be performed that focuses on educating others outside the region about the potential taconite-based aggregates hold for long-term and large-scale use.

<u>Presentations and Contacts</u>

During the first half of 2007, project findings were presented and/or discussed at the following venues:

- The Environmental Protection Agency (EPA) Region 5 in Chicago, IL, January 17, 2007.
    - Lawrence M. Zanko discussed with EPA staff how NRRI's taconite aggregate research efforts fit EPA's recycling and reuse agenda, and how those efforts relate to the beneficial recycling and reuse of sediments dredged from the Duluth-Superior harbor.
- The 80th Annual Meeting of the SME Minnesota Section and 68th Annual University of Minnesota Mining Symposium, April 17-18, 2007, Duluth, MN;
    - Zanko made a PowerPoint presentation, titled, "The Aggregate Potential of Byproducts Generated by Minnesota's Taconite Mining Industry: A Summary of Current Research"
- The 53rd Institute on Lake Superior Geology meeting held in Lutsen MN on May 8-13, 2007
    - Mark J. Severson and John J. Heine presented a poster (Appendix C) with an up-to-date summary on the stratigraphy of the Biwabik Iron Formation as revealed by recent logging of holes at Minntac, Hibtac, Utac, Keetac, and McKinley reserve.
- The 43rd Forum on the Geology of Industrial Minerals, May 20-25, 2007, Boulder, CO
    - Zanko made a PowerPoint presentation of a paper submitted for publication in the Forum's proceedings, titled, "The Aggregate Potential of Byproducts Generated by Minnesota's Taconite Mining Industry: A Summary of Current Research." The paper was co-authored by NRRI colleagues Donald R. Fosnacht, Mark J. Severson, Julie A. Oreskovich, Marsha Meinders-Patelke, and Steven A. Hauck.

NRRI's Economic Geology Group, via geologist and webmaster, John J. Heine, will continue to update the Taconite Aggregate website for dissemination of project information:

http://www.nrri.umn.edu/egg/TACAGG/default.htm

This website has led to new contacts in the private and public sectors, and potentially new opportunities and uses for Mesabi Hard Rock™.

Preliminary Research

Narrative: Preliminary research will involve gathering and reviewing existing aggregate research and relevant data developed by other individuals or organizations such as Federal Highways Administration (FHWA), Transportation Research Board (TRB), AASHTO, etc. This includes compiling lab test data on various aggregates and mining materials. Historic performance data will also be gathered about current utilization of taconite mining materials and comparable aggregates versus softer materials. Aggregate issues, problems, and needs – especially as related to target states – will also be identified during the preliminary research stage. For example, each state's certification process will be reviewed.

History of taconite by-product use as aggregate material

A final report, titled, "Documenting the Historical Use of Taconite Byproducts as Construction Aggregates in Minnesota – A GIS-based Compilation of Applications, Locations, Test Data, and Related Construction Information," by the NRRI's Julie A. Oreskovich an Marsha Patelke, is in preparation. A shortened version of the report has been prepared and will be submitted by July 31 for consideration for presentation at the January, 2008, Transportation Research Board (TRB) meeting in Washington, D.C. The TRB version is included in Appendix A.

Major findings regarding Mesabi Hard Rock™ include:

- 400+ usages documented in Minnesota from 1960 to 2006 (Fig. 1), including 1,120 miles of roadway pavement and fill.

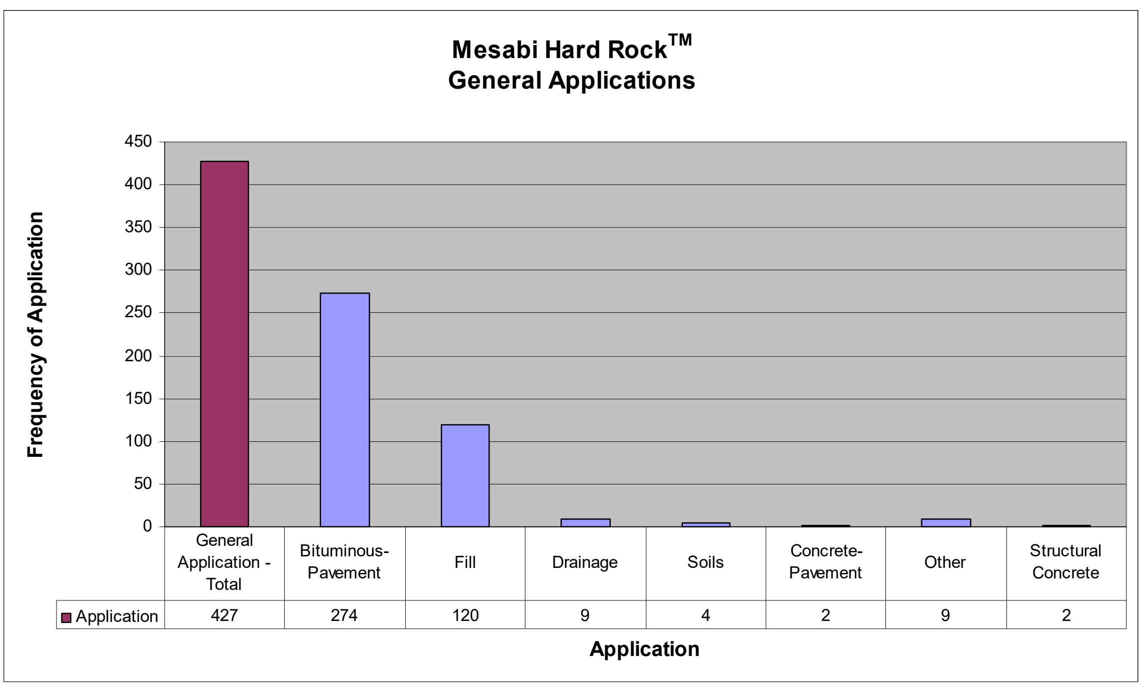

Figure 1. Mesabi Hard Rock™ general applications.

- Bituminous pavement – (~ 975 miles) – is the dominate usage. Characteristics like the hardness, durability, and 100% fracture faces make it ideal for Superpave mixes.
- Fill is the second most common useage. Close to the mines, large volumes of coarse taconite tailings are used for fill and embankment purposes.
- State projects are lead authority for road projects.

The product is a project report with a stand-alone Microsoft Access (or Excel) database and an ArcView GIS product containing mappable Mesabi Hard Rock™ usage locations with accompanying data. Topics that users can query by include: byproduct type, location, application, date, authority, and contact person. With the information, they can determine the applicability of this resource for their projects.

The compilation and documentation of historical (and new) technical information on taconite aggregate usage in Minnesota is a major and necessary part of the NRRI research program. Why? Because if Mesabi Hard Rock™ is to gain greater acceptance beyond its immediate usage area, potential end-users – especially those in the Twin Cities metro area and in surrounding states – will want documented assurance that it has, and can be, used stand-alone or blended with local aggregates to produce more competent and durable pavements.

Sample Acquisition and Preparation

Narrative: Fundamental to the research program will be ongoing availability of byproduct samples. NRRI-Coleraine will obtain and/or prepare sufficient quantities of fine and coarse taconite aggregates throughout the research program to cover all research contingencies, depending on the graded aggregate requirements for each research project. Other byproduct materials representing the mid-size range aggregates will be acquired as needed.

Based on a materials request from the University of Minnesota's Department of Civil Engineering (CivE), NRRI's Coleraine Minerals Research Laboratory (CMRL) prepared on initial sample comprised of several tons of crushed and graded aggregate for asphalt and portland cement concrete (PCC) testing (Table 1). The bulk sample originated from the lower portion of the Upper Cherty at United Taconite's (UTAC) Thunderbird Mine in Eveleth, MN. The sample was provided by Laurentian Aggregate, which has an aggregate production facility at UTAC. The sample was transported to CMRL by dump truck, courtesy of Mr. Milt Mayer of Terra Ferma Development, Iron, MN. Each size fraction prepared by CMRL was delivered in 55-gallon drums to CivE.

Table 1. Original mix design sample request.

Sieve Size (mm)	Sieve size	lbs.
38	1.5 in	550
25	1 in.	550
19	3/4 in.	550
12.5	1/2 in.	550
9.5	3/8 in.	550
4.75	No. 4	550
2.36	No. 8	550
1.18	No. 16	550
0.6	No. 30	550
0.3	No. 50	550
0.15	No. 100	200
0.075	No. 200	200

Following delivery and initial testing by CivE (see upcoming discussion in "Mix Design" section), a follow-up sample request was made to obtain more material (Table 2) from a second source. The second source is U.S. Steel's Minntac mine in Mountain Iron, MN, via Ulland Brothers,

Table 2. Follow-up mix design sample request.

Sieve Size (mm)	Sieve Size	lbs
25	1 in.	650
19	3/4 in.	2600
12.5	1/2 in.	3200
9.5	3/8 in.	3040
4.75	No. 4	3000
2.36	No. 8	1900
1.18	No. 16	1600
0.6	No. 30	1600
0.3	No. 50	1300
0.15	No. 100	1300
0.075	No. 200	500

Inc. Ulland Brothers, Inc. is an aggregate producer that has operated at Minntac for many years, and processed over 2 million tons of taconite aggregate in 2006, including Class 5 (Fig. 2) and bituminous gradations, but mostly railroad ballast for Canadian National (CN) railroad.

The next sample – like the first sample from UTAC – will come from the lower portion of the Upper Cherty (UC), and is expected to be provided to CivE by August, 2007. Several tons of finer, e.g., ¼ to ½ inch, taconite aggregate will also be acquired and processed by CMRL for use as a friction (anti-skid) course on a Mn/DOT bridge deck overlay project near International Falls, MN, planned for late August, 2007.

In early June, fifteen 5-gallon buckets were sent to the Illinois Department of Transportation (IDOT) for certification testing; testing results are expected by August. Additional samples were prepared and shipped for further evaluation by two

Figure 2. Class 5 stockpile at Minntac - Mn/DOT certified (photo taken May 9, 2007).

out-of-state companies interested in developing value-added taconite-based product lines, primarily from taconite tailings. Successful preliminary evaluation by one of the companies has led the company and NRRI to enter into a confidentiality agreement as they pursue more extensive testing.

Aggregate Testing

Narrative: Aggregate testing will be conducted to characterize the taconite mining byproducts, in conjunction with the University of Minnesota, Department of Civil Engineering, and the Minnesota Department of Transportation's (Mn/DOT) Office of Materials. This will allow taconite byproducts to be compared by themselves (or in combination with) traditional aggregates, giving potential end-users important technical and performance information.

The four bulk samples collected previously from potential aggregate horizons at two of the taconite mines have undergone physical aggregate testing by the Minnesota Department of Transportation's (Mn/ DOT's) Office of Materials in Maplewood, MN; this work is being done as part of the match to the overall EDA funding. Additional samples will be acquired and sent to Mn/DOT in the second half of 2007 as geological work continues westward.

Mn/DOT has also been testing potential alkali-silica reactivity (ASR) in concrete by performing ASTM C 1293 concrete prism tests; these tests will continue for 2 years. Previous results showed three of the four samples performing acceptably, while one sample showed unacceptably excessive expansion. These test results will aid in identifying which taconite aggregates can be used in portland cement concrete (PCC) pavement applications, and which might be limited to bituminous (asphalt) based pavements.

Geology, Mineralogy, and Chemistry

Narrative: The long-term prospects for taconite byproducts being a major source of construction aggregate will depend on material consistency. Therefore, the research program will also focus on materials that provide the best potential for long-term product uniformity. Just as geology and mineralogy control ore quality at the mines, these factors will also control byproduct quality and uniformity - within and between mines.

NRRI and mine geologists will work with Mn/DOT geologists and engineers for defining the geological and mineralogical criteria needed to best assess, sample, and characterize byproducts derived from the iron-formation for aggregate use. Site visits, field mapping, core and sample examination, microscopy, and X-ray diffractometry will all be used to accomplish this task.

<u>Geology</u>

NRRI geologists Mark Severson and John Heine have added detail to the stratigraphy of the Biwabik Iron Formation, via logging of holes at Minntac, Hibtac, Utac, Keetac, and McKinley reserve. Geologic units at most of the mines have now been incorporated into a district-wide "Rosetta Stone" that illustrates how the units compare and contrast in each of the specific mines. A reconstruction of the potential depositional environment for the Lower Cherty Unit is featured in a poster included on CD in Appendix C. This same reconstruction attempts to explain why the stratigraphic picks for the Upper Cherty/Lower Slaty contact are difficult to recognize due to a highly interfingering nature.

Severson and Heine have recently logged newly-drilled holes at Hibtac (2 holes) and at Keetac (11 holes). Several more of the newly drilled holes will be logged at Hibtac; only one more hole will be logged at Keetac. These holes will be added to the "Rosetta Stone" and the appropriate geologic correlations will be determined and updated as needed. This drill hole information will also assist in choosing aggregate horizons for sampling and characterization.

NRRI geologist Marsha Meinders-Patelke, a sequence stratigrapher, has begun looking at small-scale sedimentary features in the drill core to further refine potential depositional environments of the iron-formation. Definition of the environments could be used in the future in attempts to predict lateral changes in horizons with aggregate and iron-ore potential. Patelke has summarized her findings in a progress report; her report is presented in Appendix D.

Mineralogy

Mineralogist Tamara Diedrich of NRRI conducted X-ray diffraction (XRD) analysis of six taconite samples. The results (Fig. 3) indicate typical un-metamorphosed iron-formation. All six samples contain quartz, minnesotaite, magnetite, goethite, and siderite. In addition, they each contain one or more of the following: stilpnomelane, talc, greenalite, ankerite, and/or hematite.

As reported previously, the U.S. Geological Survey (USGS), Denver, performed X-ray diffraction (XRD) analysis

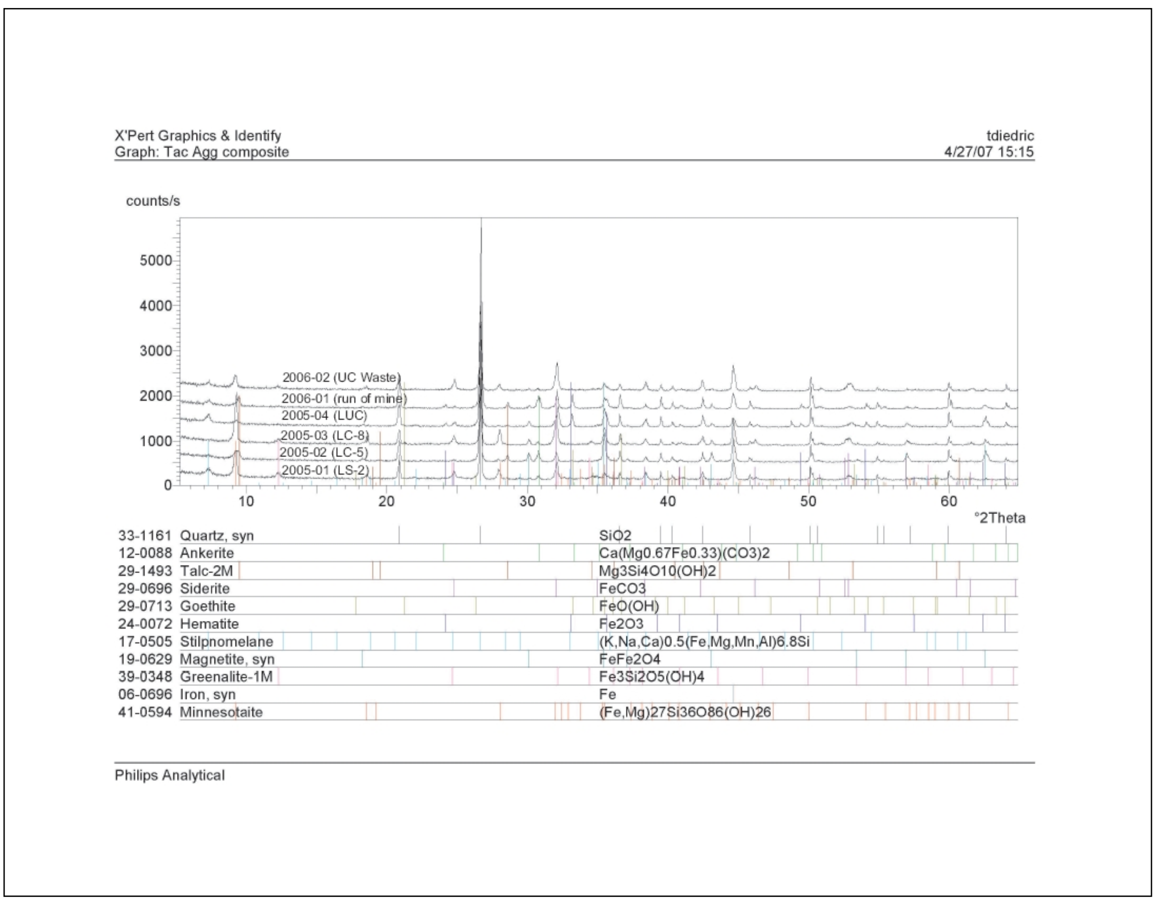

Figure 3. X-Ray diffraction (XRD) test traces of taconite aggregate samples.

on the same six aggregate samples. NRRI's analyses essentially confirm what the USGS determined, i.e., typical un-metamorphosed iron-formation mineralogy (no amphibole minerals present), with quartz and minnesotaite identified as the major minerals present.

Renewed interest in the amphibole minerals present on the eastern portion of the Mesabi Iron Range has motivated NRRI to conduct additional mineralogical research on the taconite to be used as aggregate for road construction. The mineralogy of taconite changes from east to west along the Mesabi Iron Range (Fig. 4). Contact metamorphism produced amphibole minerals on the east end; no such minerals have been observed on the western portion, where the taconite aggregate is sourced. While NRRI's XRD results confirm the established scientific consensus that there are no amphibole minerals in the western Mesabi Iron Range, we are looking more closely at these materials to ensure that they pose no risk to air quality beyond that of traditional aggregate sources.

NRRI has initiated a research program to quantify and characterize the size, shape, and mineral content of taconite particles from the areas to be sourced for road aggregate. This work will utilize scanning electron microscopy (SEM) with energy dispersive X-ray spectroscopy (EDS) in accordance with the US Environmental Protection Agency's standard operating procedures and protocols used by the U.S. Geological Survey (USGS) in Denver, CO, confirmed during a May 25, 2007, meeting with USGS Denver Microbeam Laboratory scientists by NRRI's Zanko and Diedrich (Fig. 5).

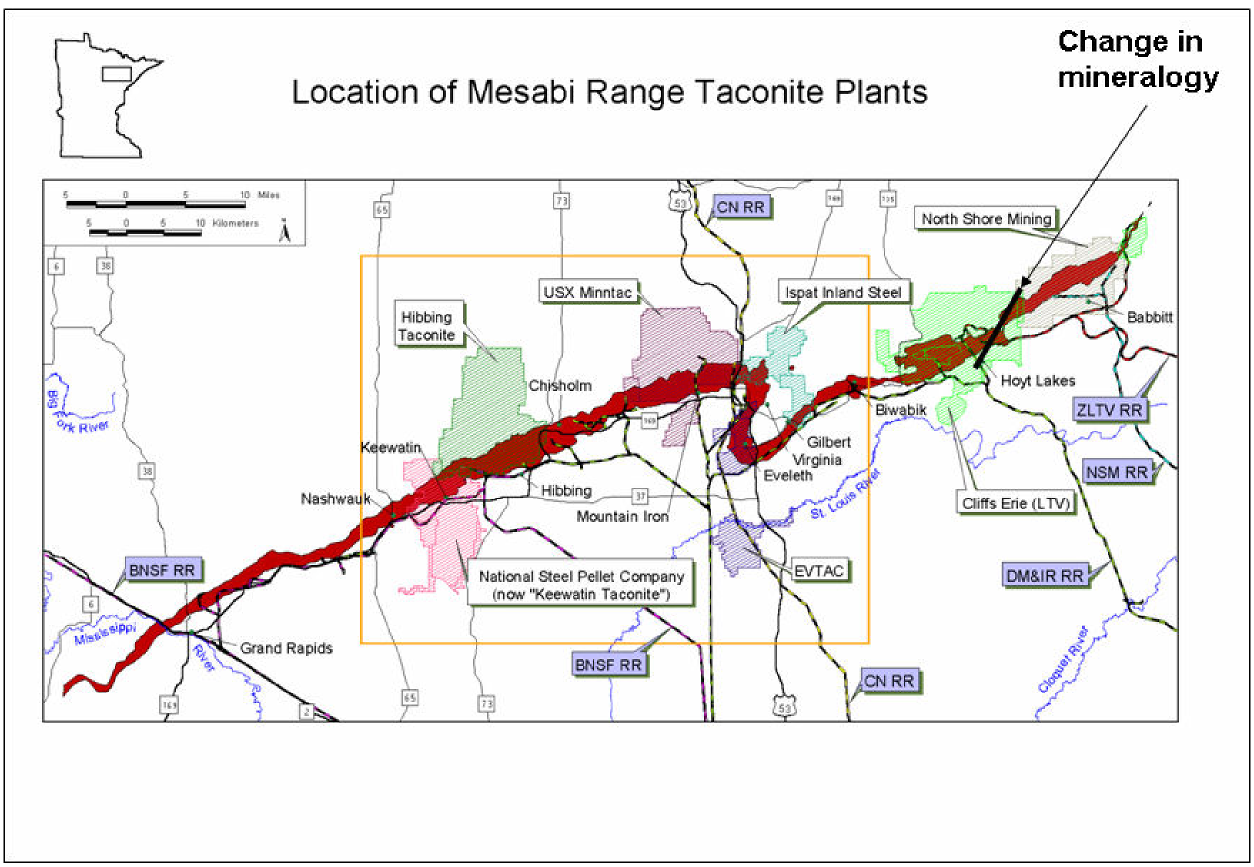

Figure 4. Change in mineralogy on Minnesota's Mesabi Range relative to taconite operation locations.

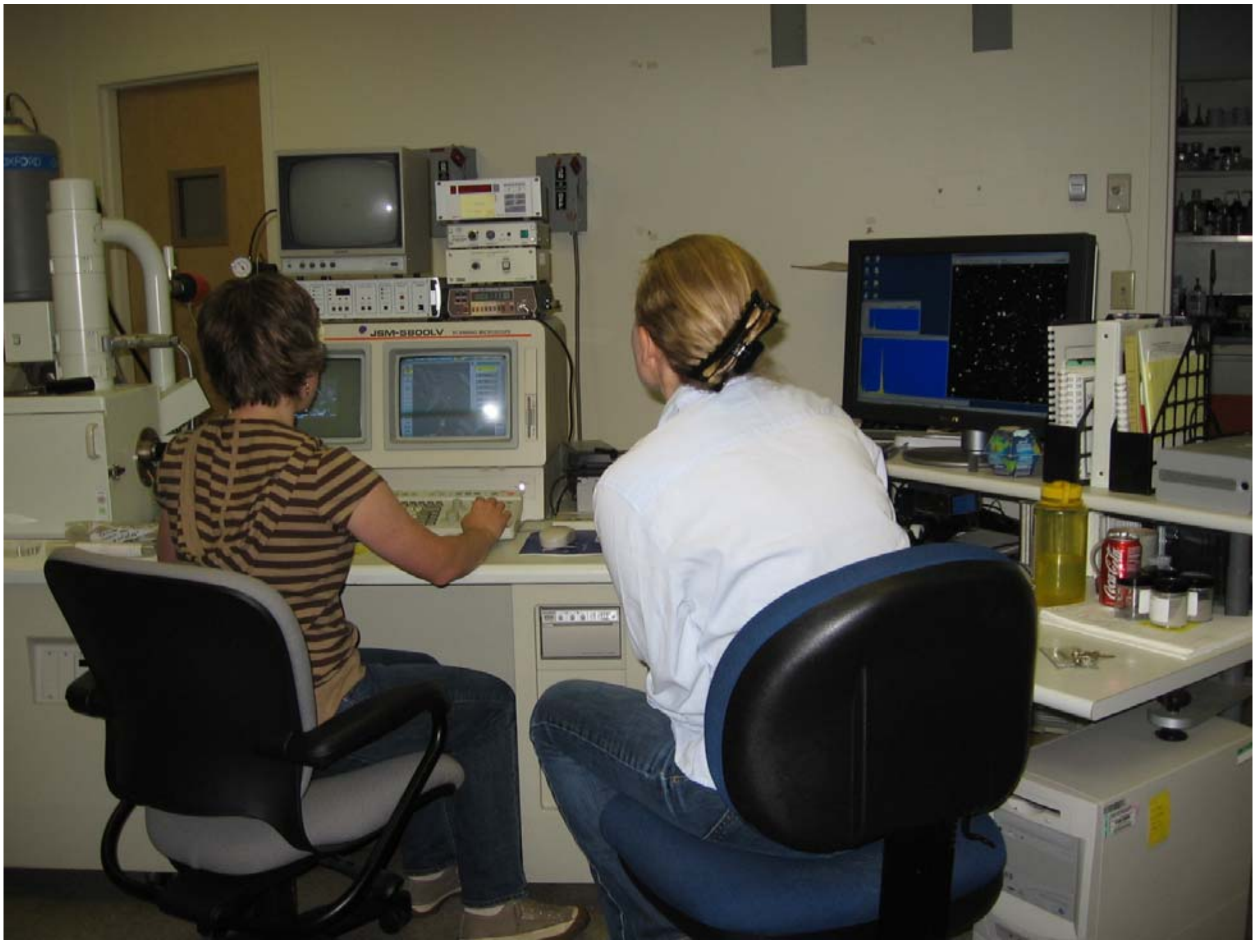

Figure 5. SEM setup at USGS's Microbeam Laboratory in Denver (on the left is Heather Lowers, USGS, and on the right is Tamara Diedrich, NRRI)

Chemistry

NRRI obtained a hand-held X-Ray fluorescence (XRF) device that will provide supplemental chemical analysis of aggregate samples.

Mix Design

Narrative: Mix design work will largely be dictated by specific demonstration projects and products that are considered. A key part of this research will be to develop and test mix designs that: 1) use taconite aggregate exclusively; and 2) combine taconite aggregate with aggregate from other rock sources. The latter work will be important for assessing how pavement performance and durability might be improved in markets where the local aggregate quality is marginal. This will be very important in demonstrating the potential use of the materials in other parts of the region such as Iowa, Illinois, Wisconsin, Michigan, and Indiana.

The NRRI will work closely with Department of Civil Engineering faculty/researchers at the University of Minnesota's Pavement Research Institute specializing in asphalt and concrete mix design; with Mn/DOT District 1 engineers (current and retired) who have experience with using taconite byproducts in mix designs and in highway construction projects in northeastern Minnesota; and *with Mn/DOT's Office of Materials. In addition, cooperative research on mix design will be pursued with the departments of transportation from other states to develop specifications for using taconite materials with their local aggregate, e.g., by adding a more durable non-polishing taconite aggregate component.*

A key part of this research will be to develop and test asphalt and portland cement concrete (PCC) mix designs that:

- use taconite aggregate exclusively; and
- combine taconite aggregate with aggregate from other rock sources.

Asphalt specimens, like those shown in Figure 6, will undergo various physical tests and will also be used for evaluating potential microwave applications.

Initial PCC testing has been performed. Sieve analysis and particle shape classification of the provided taconite aggregate samples was performed; workability and flexural strength testing of two different PCC mixes was also performed. A report has been provided by Associate Professor Lev Khazanovich, and is presented in its entirety in Appendix B.

Innovative Concepts/Uses

Pothole patching compounds

Narrative: Preliminary research by NRRI scientists showed that certain taconite byproduct materials can be used in non-asphalt based cold-mix pothole-patching compounds. Potholes are a nationwide problem, especially in northern climates.

Figure 6. Asphalt pavement specimens at the University of Minnesota's Department of Civil Engineering.

The most common petroleum-based "throw-and-go" formulations are marginally effective and often perform poorly. NRRI believes its formulation is a superior product. Limited field-testing of the patching product shows it to have excellent potential (see photos on following page). The research program will focus on developing optimal mix formulations, expanded testing (laboratory and field demonstrations), and performance monitoring.

Work is currently being conducted at NRRI to develop a taconite-based pothole patching compound. This compound does not contain asphalt and, thus, can be used year-round in road repair. From January to June, 2007, basic research was conducted to understand the role of taconite in cementing the compound. Through experimentation, we are optimizing the formulation. X-ray diffraction, optical microscopy, and scanning electron microscopy are being used to characterize the taconite cement.

Current research is being directed towards controlling "workability" with the intent of developing two formulations. One of these could be described as a "taconite cement" concrete that would be mixed and applied in a manner similar to a traditional cement concrete. A second product is a slow-setting (or non-setting) product that is heat activated. This work converges with the research on microwave absorption by taconite; in theory, the heat source could be a mobile microwave unit.

<u>Microwave heating (pavement conditioning/annealing), pothole patching, and de-icing</u>

Narrative: Joint research conducted by NRRI has shown that taconite is an excellent microwave absorber. This characteristic means that pavements or paving products that contain taconite aggregate have the potential to be heated by a mobile microwave unit. This has implications for microwave-enhanced pothole patching, de-bonding ice from pavements or airport runways, and re-heating and re-compacting portions of asphalt pavements that may otherwise suffer differential compaction and rutting. Presently, the ability to efficiently re-heat asphalt pavement for re-compaction and/or annealing is not readily available.

The microwave research program will start with comprehensive bench and lab-scale testing to better define optimal microwave and material parameters for all three paving applications. This would be followed by a period of scaled-up pavement testing and safety checking using a larger microwave unit. The ultimate goal will be to vehicle-mount a larger unit for use in actual mobile field tests. These tests could take place at NRRI-Coleraine, on a Coleraine city street, in Duluth, or at Mn/DOT's MnROAD facility.

NOTE: Project consultant, Dr. David M. Hopstock, and his subcontractor, David P. Lindroth contributed significantly to the following summary.

Further progress was made in installing the 15-kW, 2.45-GHz Microdry microwave generator at the NRRI laboratory in Duluth. Troubleshooting was carried out on the various circuits in the required sequential order. Although this involved a fair amount of time and frustration, all of the problems were eventually identified as minor ones and corrected. Among the problems identified and corrected were a nonfunctioning air flow switch that needed to be replaced, a burned-out indicator bulb, and two dirty, immobilized rotating cooling water flow indicators. All circuits are now functioning up to the ultimate element — the magnetron tube which actually produces the microwaves. This will be tested, operated, and calibrated once the water-flow calorimeter is set up and the waveguide and screen room installations are completed.

In laboratory testing, heating rates were measured in the 1-kW microwave oven on plaster-of-Paris specimens containing -8+16 mesh size fractions from the two bulk samples not previously tested — LUC and LC-8. Heating rates were also measured on four reference materials considered to be representative of "standard" road construction aggregate materials:

(1) Sample BLS: a light yellowish-brown limestone from the Edward Kraemer & Sons quarry in Burnsville, MN.

(2) Sample MGR: a pink granite from the Meridian (now Martin-Marietta) aggregate quarry near St. Cloud, MN.

(3) Sample QTZ: reddish-colored Sioux quartzite from a quarry near Fairmont, MN.

(4) Sample TRP: dark gray basalt from the Dresser Trap Rock quarry near Dresser, WI. The immediate source was quarter-inch (-4+50 mesh) bituminous aggregate (designated FA-2) taken from the MnROAD stockpile.

In the chart below (Fig. 7), smoothed microwave heating curves are shown for the four taconite bulk samples and for the four reference materials. All of the heating tests, with the exception of the "blank" tests, were done on plaster-of-Paris specimens containing 40 grams of -8+16 mesh aggregate, corresponding to 52 ± 2 weight percent aggregate in the specimen. The quartzite and granite specimens heated just slightly faster than the "blank" 100% plaster-of-Paris specimens. The next-lowest heating rate was observed with the limestone specimens. The somewhat enhanced microwave absorption was probably a result of the iron oxide minerals (probably goethite or

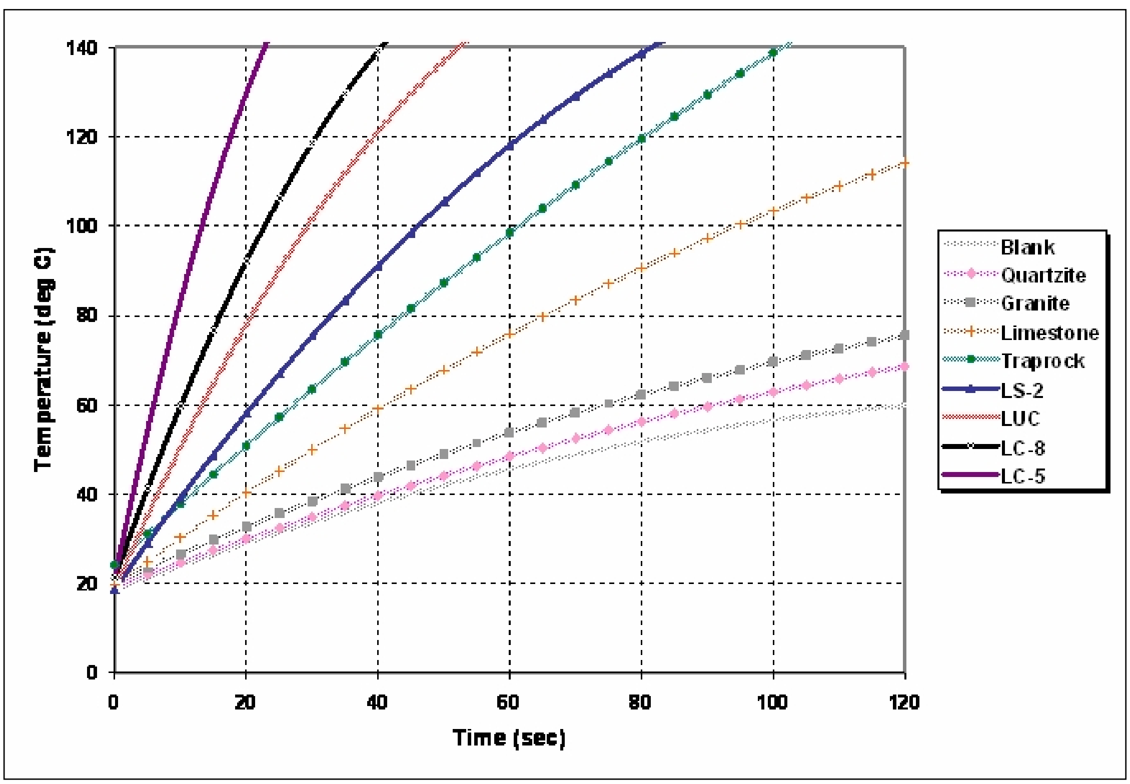

Figure 7. Heating rates of taconite aggregate and conventional aggregate.

hematite) or iron-carbonates that gave the rock a yellowish-brown color. The best microwave absorber of the reference materials was basalt or traprock. This is not surprising, because basalt may often contain a percent or two of magnetite and/or ilmenite.

All of the taconite samples absorbed microwaves more effectively than all of the reference materials. Sample LS-2 with the lowest magnetite content (3–4%) absorbed only slightly more effectively than the traprock. Sample LC-5, with a very high magnetite content of 32–33% absorbed the most rapidly. The other two samples were intermediate in magnetite content and in microwave absorption. There was a minor anomaly in that sample LC-8, containing about 13% magnetite, heated more rapidly than LUC, which contained about 19% magnetite.

For modeling and data analysis, it is necessary to know the density (or specific gravity) and heat capacity (or specific heat) of the aggregate materials. For both the taconite and comparison "standard" road construction materials, these were determined simultaneously by heating a known weight of aggregate particles to about 100ºC, pouring the particles into a known volume of water at room temperature, and measuring the resultant temperature of the water and total volume of water plus particles. For density determination, this method gave results agreeing closely with literature values for the same or similar materials. The accuracy of density determinations is estimated to be ±0.02 g/cm3. Results are given in Table 3.

Table 3. Density of aggregate materials.

Rock Type	Sample Designation	Density (g/cm3)
Taconite	LC-5	3.33
Taconite	LC-8	3.05
Taconite	LS-2	2.94
Taconite	LUC	3.12
Quartzite	QTZ	2.63
Granite	MGR	2.61
Limestone	BLS	2.70
Traprock	TRP	2.98

The calculated heat capacity values showed a high degree of scatter. In addition, values obtained by means of 240-g aggregate samples in 250 ml graduates were higher than those for 40- to 50-g samples in 50 ml graduates. Overall the calculated values were generally higher than expected from literature values. This is puzzling, because the obvious sources of error in using this method — heat loss to the glass cylinder, incomplete equilibration of temperature between the particles and the water, etc. — would tend to give low values of heat capacity, not high. Instead of the data obtained by this method, we will probably use estimated values of heat capacity based on heat capacity data determined by the U.S. Bureau of Mines using more sophisticated calorimetric equipment. The Bureau also produced thermal diffusivity data on rocks that will be useful in modeling.

Installation and preliminary testing has been successfully completed for the 15-kW, 2.45-GHz Microdry microwave generator and screened test enclosure at the NRRI laboratory in Duluth (Fig. 8). The University of Minnesota radiation safety officer inspected the installation and was favorably impressed by the attention given to safety considerations. Only a few minor changes, such as adding a fire extinguisher and signage, were suggested. The biggest remaining need is for a ventilation hood to exhaust fumes that may be generated within the test enclosure.

Preliminary calibration work was done with a flowing-water calorimeter attached to the end of the waveguide. The measured power output of the microwave generator exceeded that indicated by the panel meter by 33% at the 3 kW level, by 22% at 6 kW, and by 8% at 9 kW.

A sample holder to be placed in the waveguide between the generator and the terminating calorimeter was fabricated from stainless steel. Rectangular test specimens (85 x 42 mm x 26 mm thick) were sawn

Figure 8. Successful operation and leakage monitoring of 15kW microwave unit and test chamber (in the foreground is David Lindroth, and in the background is David Hopstock, Ph.D., of David M. Hopstock and Associates, LLC).

from cylindrical compressed asphalt test samples containing granite as the aggregate. At the 3.0 kW power level (as indicated on the panel meter), reflected power was 1.2 kW. The test specimen became hot enough to generate fumes and partially disintegrate within less than 30 seconds. Specimens with taconite as the aggregate will heat more rapidly. To generate reliable data on microwave absorption and penetration depth, it will be necessary to use artificial test specimens with a high-temperature-resistant binder, such as plaster-of-Paris, and to operate at the lowest reliable power levels.

During this period we also received an e-mail inquiry from Xiangwei Tang of the Witol Highway Equipment Maintenance Company Ltd. of mainland China. This company already produces trucks equipped with high-power microwave generators and antennas, which are used for repair of asphalt highways. He was interested in our work on the use of microwaves for deicing. We explored the possibility of cooperative research, but — because of combined distance, language, and financial barriers — have not been able to develop a workable plan for such cooperation.

After weighing the available options, a decision was made to pursue building a wheeled portable microwave applicator, roughly the size of a power lawnmower. The unit, developed as a prototype, would likely use 220-volt power and apply 3 kilowatts of microwave energy. We believe that this prototype would be useful for field-demonstrating the concepts of microwave deicing and microwave pothole repair, based on our work using the lab-based 15-kW generator. A planning and design meeting will take place in late July.

Demonstration Projects

Narrative: Demonstration projects will be a key component of the overall taconite aggregate research program. The use of the material in actual operating applications is the best method of demonstrating its potential as a long lasting durable roadway material. Demonstration projects are intended to reflect a variety of surface applications, climatic conditions and traffic volumes and will generate practical data in real life settings.

MnROAD Field Demonstrations

Narrative: Mn/DOT's MnROAD facility in Albertville, MN (40 miles northwest of the Twin Cities), is a cold region-testing laboratory that is unique to the world. The MnROAD facility is an excellent pilot- to full-scale field research platform for testing and monitoring a variety of construction aggregate applications that use taconite aggregate.

The terms of the sub-award for Mn/ROAD that were mutually satisfactory to the University, Mn/DOT, and EDA were finally agreed upon in January, 2007. Major reconstruction work is planned for the MnROAD facility, especially in 2008, and taconite aggregate materials will have significant usage.

Field Demonstrations

Narrative: A vitally importantly part of the project will include practical real life demonstration of the use of the material in partnership with targeted state Departments of Transportation (DOT). Such field demonstrations will help advance long-term taconite byproduct usage for transportation infrastructure projects, particularly for markets outside of Minnesota. This will entail obtaining the necessary agency approval for construction purposes, certification and acceptance of the material as a premier aggregate resource with certifying agencies and within the construction industry, and resolving transportation issues that may exist in bringing the materials to the specific targeted markets.

These demonstration projects will assist in accurately assessing the quality and performance of taconite as a bituminous and concrete aggregate material in terms of its fundamental chemical, physical and mechanical characteristics. Demonstration activities will also include market development, field consulting, manufacturing of the material to pavement specifications, the development of a thorough testing and evaluation protocol, and the development of transportation, materials transfer, and identification and procurement of sites necessary for storage of the material near demonstration locations.

Early in 2007, significant progress was being made toward conducting a major paving demonstration project in the Chicago area with the Illinois Department of Transportation (IDOT), using several thousand tons of Minnesota taconite materials. Progress included working out logistical issues with IDOT, the Illinois contractor, the Minnesota contractor, and the shippers. However, a mid-March conference call with IDOT revealed that the highway project in Elgin, IL, where the proposed demonstration was to occur, was postponed due to IDOT budget constraints. Efforts are still being made to conduct a major demonstration project during the 2007 construction season.

A smaller project is under consideration using a crushing undersize material generated by Ulland Brothers, Inc., from their Minntac operation. The screened product would be used as a friction course on a Mn/DOT bridge deck overlay job on Trunk Highway 11 near International Falls later in August, 2007, in combination with a urethane-based coating product marketed by a local (Proctor) company, Superior Coating Specialists. An estimated 5-10 tons of this screened aggregate will be brought to the jobsite in 55 gal drums. The objective is to decrease slippery conditions on the bridge caused by paper mill stack emissions and atmospheric conditions, i.e., icing.

The planned International Falls demonstration will be similar to the Colorado bridge deck demonstration that was done in the spring of 2006, using coarse taconite tailings. Photographs of the Frisco, Colorado, bridge deck are shown in Figure 9, one year after installation. The photograph was taken on May 25, 2007.

Transportation Logistics and Economics

Narrative: One of the basic limiting factors in expanding the use of taconite by-products is the cost of bringing the materials to the market locations. The transportation logistics questions associated with creating a huge new market for taconite mining by-products must be resolved in order to fully implement this opportunity. Throughout the research program there will be a focus on developing various options to move large tonnages of by-product materials to desired markets in a cost efficient manner using the intermodal transportation options, e.g., rail, barge, and shipping, which exist in the Great Lakes region. That is why continuing input from – and collaboration with – private and public sector transportation researchers and professionals who specialize in these areas will be a significant part of the research effort.

On April 10, 2007, a follow-up meeting of the project's Transportation and Logistics Working Group was held in Hinckley, MN (midway between Duluth and the Twin

Figure 9. Frisco, CO, bridge deck one year after installation (left), and close-up of coarse taconite tailings used for friction course (right). Photographs taken on May 25, 2007.

Cities), focusing on transportation logistics and economics. Attendees included: Dan Jordan, Iron Range Resources (IRR); Stacey Carlson, Great Lakes Maritime Research Institute – University of Minnesota Duluth (GLMRI-UMD), for Richard Stewart; Betty Juntune and Patrick Dorin (American Surface Lines/RailMate); Jill Thomas, Minnesota Asphalt Paving Association (MAPA), for Richard Wolters; Denny Johnson and Bob Gale (Mn/DOT Freight Office); David Christianson (Tinklenberg Group); Dick Kiesel (CMRL); and Pamela Sarvela, Tamara Diedrich, and Larry Zanko (NRRI).

Meeting topics included: taconite aggregate program update; a discussion of potential Minnesota demonstration projects; and an update on RailMate, a bi-modal (truck/rail) system.

On June 26, 2007, NRRI attended an equipment demonstration of RailMate. The RailMate system will likely be used for one or more aggregate demonstration projects in late summer or early fall of 2007, moving aggregate product from a taconite mine to one or more Twin Cities destinations and/or to Duluth, MN.

Communications and Marketing

Narrative: A variety of aggregate materials are used throughout the Midwestern region of the United States in highway construction. Taconite by-products will have to compete with these existing materials based on both their physical attributes and the net value they will bring to a road project. In order to position the various potential products that can be used from the Minnesota Iron Range, a significant education and marketing effort will be required. This will entail developing communication pieces that can address the issues associated with substituting taconite based products for local materials, the handling and logistics issues will be overcome in bringing the materials to the desired locations, and the issues on how to incorporate the approval of taconite material use in local jurisdictions.

In addition to presenting papers, NRRI hosted an exhibitor booth at both the 80th Annual Meeting of the SME Minnesota Section and 68th Annual University of Minnesota Mining Symposium, April 17-18,

Figure 10. Mesabi Hard Rock - NRRI exhibitor booth and list of exhibitors for 43rd Geology of Industrial Minerals Forum, Boulder, CO, May 20-25, 2007.

2007, in Duluth, MN; and at the 43rd Forum on the Geology of Industrial Minerals, May 20-25, 2007, Boulder, CO. An information brochure with CD and small bags of aggregate samples were made available to attendees of both events. Figure 10 shows the Mesabi Hard Rock™ - NRRI booth setup, and a poster listing all of the exhibitors, at the 43rd Forum in Boulder.

New contacts were made at both events, and have led to further communications relative to potential projects that could make use of Mesabi Hard Rock™, even in a project as distant as the Pacific coast.

The Tinklenberg Group was contracted to play a significant role in these efforts, and their ongoing activities and efforts are summarized in Appendix E.

Upcoming Meeting/Conference Paper Presentations

As described previously, a paper titled, "Documenting the Historical Use of Taconite Byproducts as Construction Aggregates in Minnesota – A GIS-based Compilation of Applications, Locations, Test Data, and Related Construction Information," by the NRRI's Julie A. Oreskovich and Marsha Patelke, has been prepared and will be submitted by July 31 for consideration for presentation at the January, 2008, Transportation Research Board (TRB) meeting in Washington, D.C.

The paper is presented in its entirety in Appendix A.

APPENDIX A:

Documenting the Historical Use of Taconite Byproducts as Construction Aggregates in Minnesota – A GIS-based Compilation of Applications, Locations, Test Data, and Related Construction Information

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July 30, 2007

word count – 5224
figures – 9

ABSTRACT
Aggregate shortages are causing increasing concern for population centers across the country. Meanwhile, Minnesota's taconite mining industry generates over 125 million tons of mining and processing byproducts annually that hold aggregate potential of traprock quality. Materials such as blast rock, coarse crushed rock and coarse tailings (collectively known as Mesabi Hard Rock™), have been staples of northeastern Minnesota road construction for over four decades. Infrastructure is already in place to move these materials to markets throughout the country to augment local aggregate resources.

Because these highway construction applications are not widely known outside of northeastern Minnesota, this study was undertaken to: 1) document how and where taconite byproducts have been used; and 2) assemble related test data. Letters, interviews, site visits, and searches of archived records were the primary modes of data collection.

The product is a project report with a stand-alone Microsoft Access (or Excel) database and an ArcView GIS product containing mappable Mesabi Hard Rock™ usage locations with accompanying data. Topics that users can query include byproduct type, location, application, date, authority, and contact person. With such information, users can determine the applicability of this resource to their own projects.

Major findings regarding Mesabi Hard Rock™:

- 400+ documented usages in Minnesota from 1960 to 2006, including 1,120 usage miles of roadway pavement and fill
- Primary Usages:
  1) Bituminous pavement (hardness, durability, and 100% fractured faces ideal for Superpave mixes)
  2) Fill (free-draining, ready-made fine aggregate equivalent)
- Minnesota Department of Transportation leads usage.

INTRODUCTION

Aggregate shortages in general, as well as shortages of competent aggregates, will become increasingly prevalent in many areas of the country as demand grows and states expand or rebuild the infrastructure necessary to serve an increasing population. Large metropolitan areas such as Minneapolis-St. Paul and Chicago are particularly susceptible to aggregate shortfalls due to such factors as urban sprawl resulting in "land-locked" quarries (resource sterilization), permitting issues, and unfavorable public perceptions.

Tepordei and Bolen (*1*) put this issue in perspective as follows:

> "The total projected cumulative production of aggregates — crushed stone and construction sand and gravel — during the next 25 years is estimated to be 92 billion tons, slightly more than the total amount of aggregates mined between 1900 and 1999. These projections suggest that very large quantities of crushed stone and construction sand and gravel will be needed in the future and will have to come, at least in part, ***from resources yet to be delineated***" (our emphasis).

One solution to this growing problem is to increase the use of unconventional aggregate sources that are also, in effect, recycled industrial materials. Importantly, the use of recycled materials is encouraged under the "Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU)," Public Law 109–59—Aug. 10, 2005 119 Stat. 1787, as follows:

> SEC. 5203. TECHNOLOGY DEPLOYMENT.
>
> ''(2) GOALS.—The goals of the innovative pavement research and deployment program shall include—
>
> ''(A) the deployment of new, cost-effective, innovative designs, materials, recycled materials (***including taconite tailings*** and foundry sand), and practices to extend pavement life and performance and to improve customer satisfaction;"

Byproducts of Minnesota's taconite (iron ore) mining industry, which include blast rock, crushed taconite rock, and coarse taconite tailings (collectively known as Mesabi Hard Rock™), not only represent some of the "yet to be delineated" aggregate resources discussed by Tepordei and Bolen, they also represent the types of recycled materials encouraged by SAFETEA-LU. Comparable to trap rock in quality, these materials have been staples of the road construction industry on Minnesota's Mesabi Iron Range for over four decades (*2*).

The Mesabi Range – the historic iron ore/taconite mining district of northeastern Minnesota – extends nearly 100 miles from Grand Rapids at its southwest to near Ely at its northeast terminus (Fig. 1).

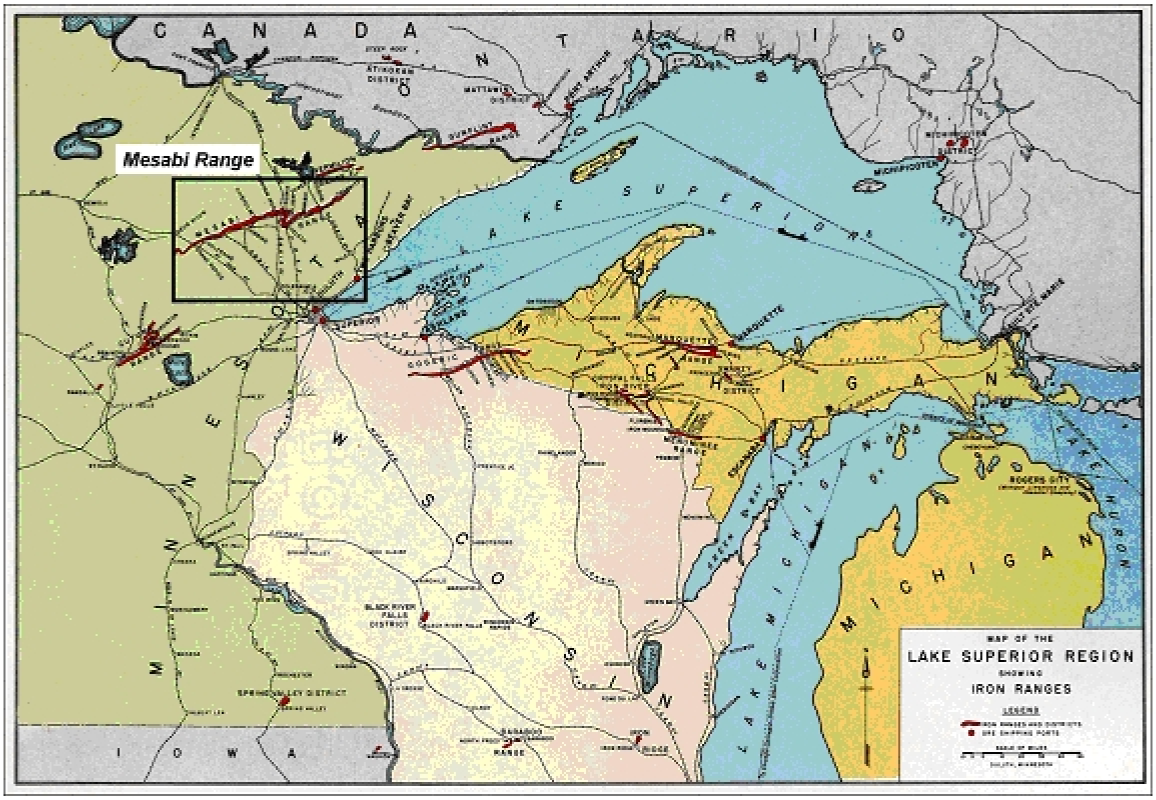

FIGURE 1 Mesabi Range (boxed area) relative to historic Lake Superior region iron ranges. Map source: Oliver Iron Mining Division, United States Steel Corporation (*3*).

There are currently six operating taconite mines and processing facilities (Fig. 2) that together generate about 125 million tons of these mining and processing byproducts every year, a figure that is more than double the entire state's annual aggregate usage. A seventh, Cliffs Erie (LTV), closed in 2001. While not all of these taconite materials are suitable or available for use, the potential is still enormous.

Since the year 2000, the Natural Resources Research Institute (NRRI), University of Minnesota Duluth, has been investigating how these vast quantities of taconite mining byproducts can be used for construction aggregate purposes on an expanded basis. With major support from the U.S. Department of Commerce, Economic Development Administration, the NRRI is presently conducting a comprehensive three-year (2006 - 2008) research and demonstration program designed to: 1) identify new and economically viable uses for Minnesota Iron Range taconite aggregate, i.e., Mesabi Hard Rock™, material in road construction, road repair, and other applications where crushed stone aggregate is needed; and 2) conduct demonstration projects inside and outside Minnesota, including several targeted Upper Midwest states (*4*).

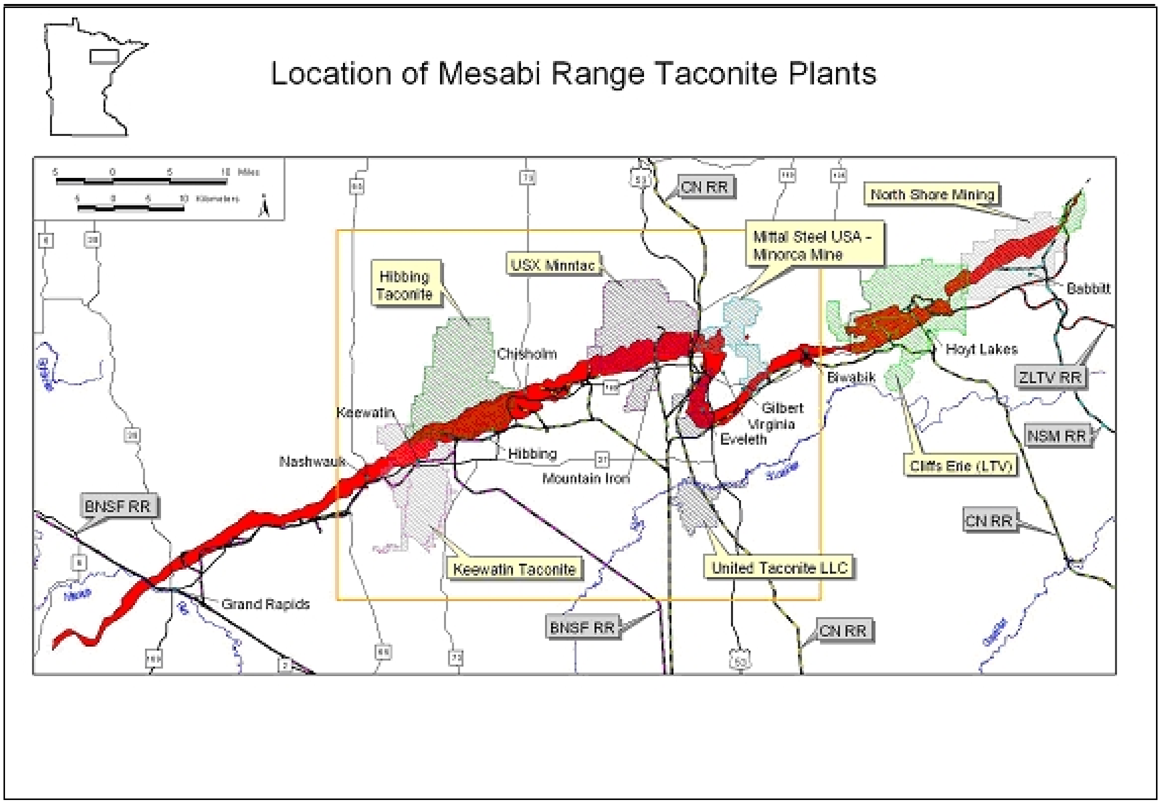

FIGURE 2 Location map of Minnesota Mesabi Range taconite mining operations. The light-colored box indicates focus area of NRRI's 2000-2002 coarse tailings study (modified from Zanko et al. [*5*]).

The compilation and documentation of historical (and new) technical information on taconite aggregate usage in Minnesota – the subject of this study – is a major and necessary part of the NRRI research program. Why? Because if Mesabi Hard Rock™ is to gain greater acceptance beyond its immediate usage area, potential end-users – especially those in the Twin Cities metro area and in surrounding states – will want documented assurance that it has, and can be, used stand-alone or blended with local aggregates to produce more competent and durable pavements.

To do so, a GIS product was produced documenting the historical use of taconite byproducts as construction aggregate in Minnesota, with particular attention paid to its use in road construction. Included in the GIS product are the various available aggregate products, their applications, locations of use, and supporting documentation including, where available, Minnesota Department of Transportation (Mn/DOT) design plans and specifications, and test data. The objective is to provide an accessible means to engineers, designers, contractors, and others of determining the applicability of taconite aggregate products for their individual needs. The remainder of this report is devoted to: 1) describing how this objective was achieved; and 2) presenting the study's findings.

OVERVIEW

Mesabi Hard Rock™ Products

There are three basic byproducts ("wastes") from taconite mining and taconite pellet production that comprise Mesabi Hard Rock™:

1) Taconite Blast Rock
2) Coarse Taconite Aggregates
3) Coarse Taconite Tailings.

Blast rock is "waste" taconite rock that must be drilled, blasted and removed to get to the mineable taconite ore. Blast rock can range in size from large slabs to fine powder. It generally refers to material that is greater than 6 inches in size. Blast rock can be used for armor stone or rip rap, or it can be processed to specification to produce ballast material and other coarse taconite aggregate fractions.

Coarse taconite aggregates (coarse crushed rock) are "waste" taconite rock that has undergone crushing or grinding to meet a particular aggregate specification (i.e., ballast, - ¾ inch, - ½ inch, Class 5, etc.). This material is derived from further processing of blast rock, either by crushing to produce edged particles or autogenous mill grinding to produce rounded particles.

Coarse taconite tailings are a byproduct or "waste" produced during the concentrating portion of the taconite pellet production process. They are by far the most frequently used Mesabi Hard Rock™ product. Coarse taconite tailings are a market-ready product (fine aggregate equivalent) that is – 3/8 inch in size and contains very low fines (- 200 mesh). A very consistent product is generated by three of the taconite producers – Minntac, Mittal Steel – Minorca Mine, and United Taconite – as a result of using a process that separates coarse tailings out of the system before they can be joined with the fine tailings produced by further crushing. The amount of fines (- 200 mesh) contained in the coarse taconite tailings from these three operations is generally < 2.5% (*5*). Coarse tailings are *not* separated from fine tailings in the Hibbing Taconite (Hibtac) and Keewatin Taconite (Keetac) concentrators. Combined tailings flow as a slurry to the tailings basin in two flumes at Hibtac, and through a pipe at Keetac. While some size separation is achieved as the larger particles settle out of the slurries near the points of entry to the basins, coarse tailings from these two operations will necessarily have a more variable size distribution.

Mesabi Hard Rock™ Usage in Northeastern Minnesota

Highway projects in northeastern Minnesota routinely utilize Mesabi Hard Rock™ as construction aggregates. Many segments of US Trunk Highway 53 (US TH53) from Duluth to International Falls are paved with bituminous mixes containing taconite byproducts. This is also the case for other major highways in the region, including Minnesota Trunk Highway 61 (MN TH61) from Duluth up the North Shore of Lake Superior to Grand Marais, MN/US TH169 from Ely to Grand Rapids, and MN TH1 from Ely to Illgen City on the shore of Lake Superior (Fig. 3). US TH 53 and MN TH61 are high volume roads with 2005 reported annual average daily traffic rates of 571,835 and 242,800 respectively (*6*).

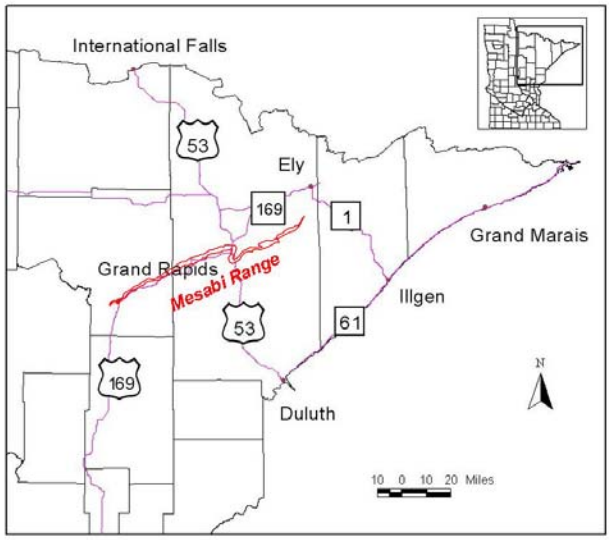

FIGURE 3 Major northeastern Minnesota highways containing Mesabi Hard Rock™.

Highway segments may also rest on a base, sub-base, subgrade and / or embankment of coarse taconite tailings, overlie culverts resting on and backfilled with coarse taconite tailings, or incorporate taconite tailings as filter rock in edge drains. In addition, coarse taconite tailings are used in bituminous mix as a crack-sealing compound. Municipalities across the Mesabi Range, as well as the city of Duluth, have used taconite byproducts in city streets for drainage, fill, subgrade, base, bituminous non-wear and wear courses, and bituminous overlays.

From Mn/DOT to the highway departments of St. Louis, Lake, and Itasca counties and the Public Works departments of local municipalities such as Virginia, Hibbing, and Grand Rapids, taconite byproduct usage in road construction has been widespread and well documented over the past forty-plus years. Identification of existing roadways and structures that incorporated taconite byproducts into their composition provides excellent opportunities for conducting follow-up field observations and locating historical source material from which to draw test cores. Evaluation of such cores can help determine how these materials wear over time and under severe climate conditions, as some structures have been in place for over forty years. Relating structural performance to physical test data, as collected from archived records, can enable prediction of future performance, and yield a historical base on which to proffer these materials as suitable aggregate materials for out-state and out of state areas.

RESEARCH METHODS

Documenting where Mesabi Hard Rock™ has been used as construction aggregate began with sending out an introductory letter describing the project and its prescribed outcome. Letters were sent to over 50 individuals representing Mn/DOT; St. Louis, Lake, and Itasca counties; northeastern Minnesota municipalities; contractors; engineering firms; testing firms; and industry representatives.

The letters were followed up by phone contact seeking usage information, anecdotal as well as documented, and supporting materials such as maps and test data. Responses were very positive, and generated further contacts, resulting in over 100 individuals contributing to this product.

Mn/DOT allowed access to its construction files, which provided a wealth of project and construction-related data. In addition, Mn/DOT District 1, Duluth, hosted a meeting of current and retired engineers and others that had been involved in using taconite byproducts on state road projects. Their recollections and descriptions of, and hands-on experience with, taconite-based aggregates provided valuable insights to the project. Discussion centered on usage locations, applications, product value and handling characteristics.

All of the data collection tools and methods just described, i.e., a copy of the introductory letter, a listing of contributing individuals and their corresponding affiliations, and highlights of various discussions, and other supporting information/documentation, are also available as supplemental project products.

DATA COMPILATION AND GIS PRODUCT

Project Data Compilation

Information regarding the past use of Mesabi Hard Rock™ was obtained from interviews and archived and current project files. Historical usage data collected for this project were assembled into the following two main products:

1) Mesabi Hard Rock_Usage Spreadsheet / Database; and
2) EDA MHR Usage 0607 ArcView GIS Product (map and shape files).

Mesabi Hard Rock Usage Spreadsheet / Database

An inventory of the reported historical usages of taconite byproduct aggregates was created in the Mesabi Hard Rock Usage Excel spreadsheet to document all usage data obtained from this study. Data may be project- or site-specific and reference a specific mappable location, or it may be more general in nature and reference area. Data entered include: project name, project type, project location, project number, project size, type of product used, test data availability, application and source of information. Each data item has been given a NRRI unique number which consists of the county code plus 3 digits. In addition to the project data, definitions and a listing of available test data are also included in the Mesabi Hard Rock Usage spreadsheet.

EDA MHR Usage 0607 ArcView GIS Product

A map (EDA MHR Usage 0607) was created in ArcView 3.3 format using shape files obtained from the Minnesota Department of Transportation (Mn/DOT) and the Minnesota Department of Natural Resources websites. All project data that had mappable locations were incorporated into the base map. Projects for this study appeared to fall into two main categories, roads and structures. Roads were further subdivided into road projects with known beginning and end points, and road projects with only general locations. To plot the projects, three ArcView themes were created and are included: Road – Line, Road – Point, and Structure – Point. Project data from the Mesabi Hard Rock Usage spreadsheet were then joined to project locations using the NRRI unique number.

Many of the project files obtained from Mn/DOT included standardized forms containing project field data (gradations, oil content in bituminous, etc.). Copies of all maps, test data and other related documents were scanned so that copies of the original documents are available.

PROJECT FINDINGS

Data Collection Results

Over 400 usage records for Mesabi Hard Rock™ have been entered into the project spreadsheet / database as a result of contributions from over 100 individuals. Data were obtained through phone conversations (anecdotal), maps, project listings, and original project files containing design specifications, test sheets, and construction diaries. These records span the time from 1960 to 2006, a period of 46 years.

Multiple usage records may exist for a given geographic location if multiple byproducts (i.e., coarse crushed rock and coarse taconite tailings), multiple applications (i.e., bituminous wear / non-wear, base, sub-base, and /or subgrade), or multiple years (i.e., 1970 and 1995) were involved. On occasion, multiple usage records may have been created for a specific project when more than one source provided pertinent information on the project. This was done in an effort to attribute the information to the source for reference purposes.

Data Trends

Product Usage Distribution

As seen in Figure 4, the predominant usage for Mesabi Hard Rock™ over the past 46 years has been in bituminous pavement. Three factors have contributed to this. First, coarse taconite tailings are market-ready "as is," i.e., no additional processing is required for them to meet specifications as fine aggregate equivalent or select granular borrow. Second, the mines long considered coarse tailings to be a waste product, so it was often available at a minimal cost. Changing times and economic conditions have now placed value on this byproduct. A third factor was the 2361TT (taconite tailing) overlays that were predominant from the 1970s into the 1990s. These overlays used 100% taconite tailings and produced a strong durable surface with excellent skid resistance properties. Taconite tailing overlays were laid down throughout Minnesota in the 1970s in areas as diverse as Minneapolis, Willmar, Moorhead, Duluth, and the Mesabi Iron Range. Some of these overlays are still in place. A down side to the 2361TT mix was the higher oil content (7.5 %) required due to the angular nature and low fines content of the tailings.

In more recent years, taconite tailings have been incorporated as one of several components in bituminous mix design. In 2001, the major highways in the vicinity of Eveleth, Gilbert, and Virginia received taconite tailing overlays. While some contained 100 % taconite tailings, others contained varying percentages of them. An advantage to working with coarse taconite tailings, in addition to the wear properties they impart to pavements, is that they provide excellent control of volumetric properties in mix designs, making it possible to pass all state and county parameters (Gustafson, D., pers. comm., 2006).

Coarse crushed taconite rock aggregates have only come into play during the last decade. While taconite operations have brought contractors in for the past thirty years to crush waste rock for on-site use, with little thought given to outside sales.

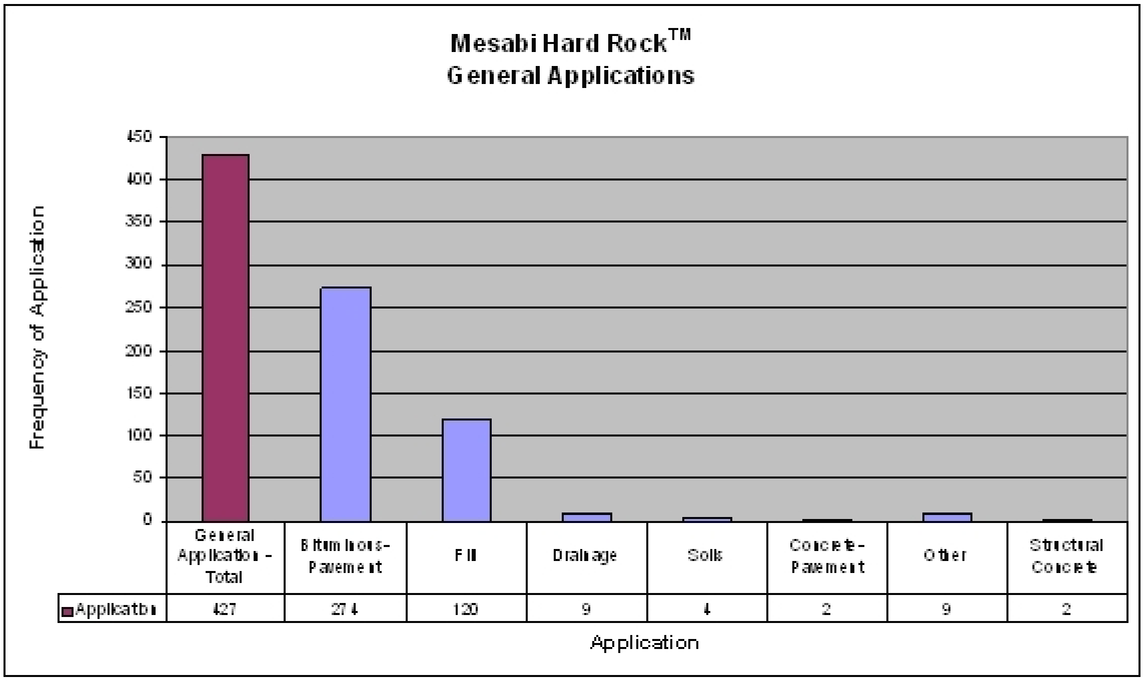

FIGURE 4 Mesabi Hard Rock™ general applications.

Ulland Brothers, Inc., headquartered in Cloquet, Minnesota, has operated an aggregate production facility at Minntac since 1989 (Licari, A., pers. comm., 2007). This began as an operation to produce railroad ballast. Coarse crushed rock (specifically, undersize material called "ballast rejects") became a source of road aggregate material. Today, Ulland Brothers is also crushing to specification to meet demands for various coarse aggregate fractions, and processed 2.3 million tons of taconite aggregate in 2006 (Klun, D., pers. comm., 2007).

Blast rock, unless further crushed to produce coarse aggregates, sees more limited use. Some has been used as armor stone for safe harbor construction along the north shore of Lake Superior and as rip rap. However, greater interest has been expressed recently for using blast rock for waterway / shore land protection applications because taconite has a higher compressive strength and specific gravity than most conventional rock; in other words, it is less likely to break down under wave action and more likely to stay in place. Blast rock has also seen growing use in landscaping applications.

Mesabi Hard Rock™ General Applications

Seven applications have been identified for the Mesabi Hard Rock™ aggregates, without regard to product (i.e., blast rock, coarse aggregate, or coarse tailings) (Fig. 4):

1) Bituminous Pavement
2) Fill
3) Drainage
4) Soils
5) Concrete Pavement
6) Concrete Structures
7) Other

In the spreadsheet / data base each application is further subdivided into general uses and specific uses.

Bituminous pavements and fills account for nearly all (92%) of the product uses and will be discussed in more detail below. A third general application is "drainage." This would include edge drains running parallel to pavements. Drainage is often a consideration in choosing coarse taconite tailings as fill. Tailings serve a dual purpose in many locations. While performing as subgrade, sub-base, or base, they also effectively drain water away from the road surface. Their typically low (<2.5 %) fines content disallows any capillary action to draw water up to the surface from below (Hill, D. M., pers. comm., 2006).

The soils application is an interesting one, unrelated to road construction. In one instance, coarse taconite tailings were used in a 50:50 mix with topsoil to alleviate drainage problems on the Virginia Golf Course. The other applications involved coarse taconite tailings that were hauled to Indiana, Ohio and Texas for use as a soil amendment in farm fields. Apparently the tailings have paramagnetic properties in addition to opening up the soils to allow root structures to grow deeper. This enables a reduction in fertilizer use. Approximately 1,200 lbs. / acre are applied every six years (Nemanich, J., pers. comm., 2006).

The "Other" category includes winter sand, landscape rock and building exterior stone. Winter sand bears mention here. Use of taconite tailings for winter sand goes back to the 1960s. It was applied on TH MN61, along Lake Superior's north shore, and other roads in Lake County. Today it is used in Mn/DOT's Virginia district in a 50 / 50 mix with road salt.

Mesabi Hard Rock™ Usage in Bituminous Pavement

Bituminous pavement usage was reported to fall into three categories: roads, airports, and parking lots. Use of Mesabi Hard Rock™ in bituminous roads was by far the dominate usage. The 100 % fractured faces of the coarse crushed aggregates and the coarse tailings, coupled with superior hardness and durability, make Mesabi Hard Rock™ ideal for Superpave mixes. One of the first Superpave projects done in Minnesota was an eighteen-mile stretch either side of Floodwood on US TH2 in the 1990s. The mix used contained 20 % taconite tailings (Olson, R., pers. comm., 2006).

The airport category is a fairly recent development for Mesabi Hard Rock™, going back to 1999. With its strength and durability, Mesabi Hard Rock™ is seeing use at small regional airports and in aprons and runways at the Duluth International Airport.

Figure 5 provides more insight into how Mesabi Hard Rock™ is being used in bituminous road pavements. These categories are based on the data as provided. It is likely that in a number of cases, what was provided as "wear course," for example, would actually fall under "overlay."

Mesabi Hard Rock™ Use as Road Fill

Mesabi Hard Rock™ has been used in all aspects of road fill, from subgrade up to base, and as embankment fill (Fig. 6). Coarse taconite tailings make up the greater share of occurrences using Mesabi Hard Rock™ as fill, being used as base, sub-base, subgrade (Class 3) and select granular. However, the coarse crushed aggregates are coming on strongly in recent years, particularly for Class 5 and Class 6 base in total reconstruction projects, as well as new construction.

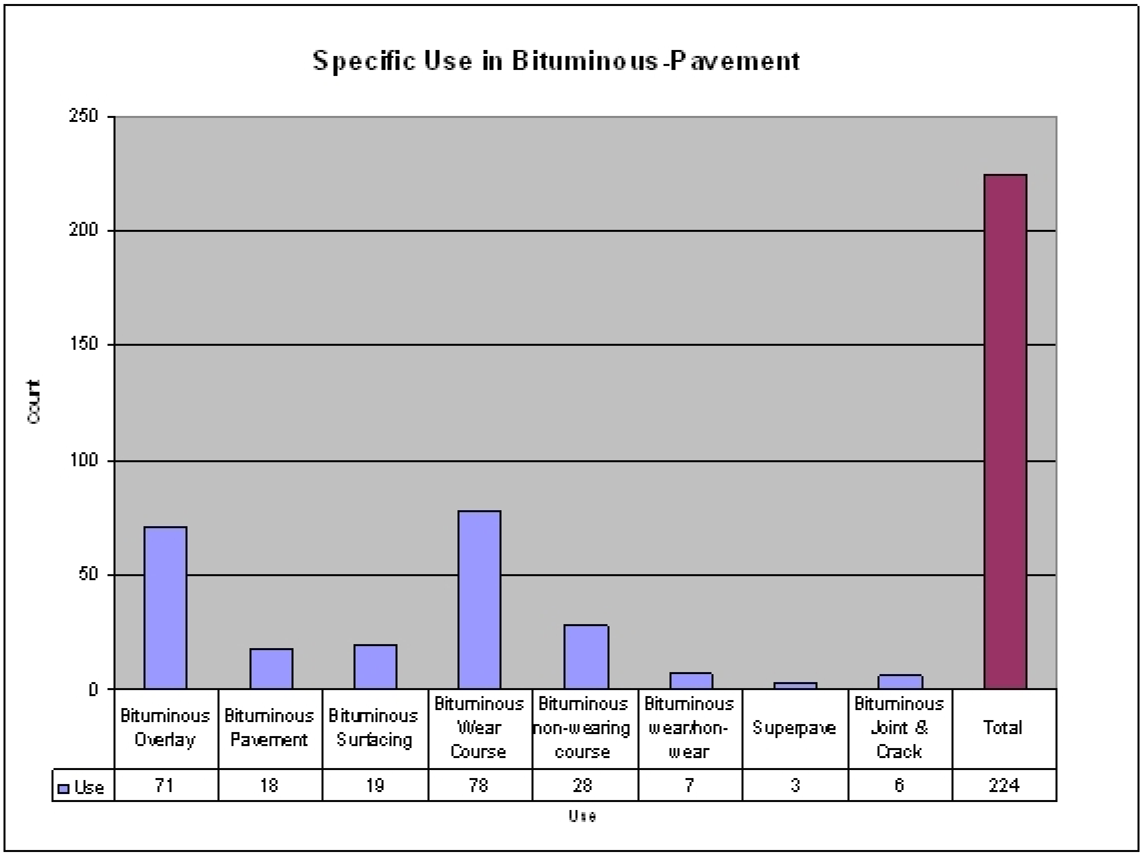

FIGURE 5 Specific uses of Mesabi Hard Rock™ in bituminous pavement.

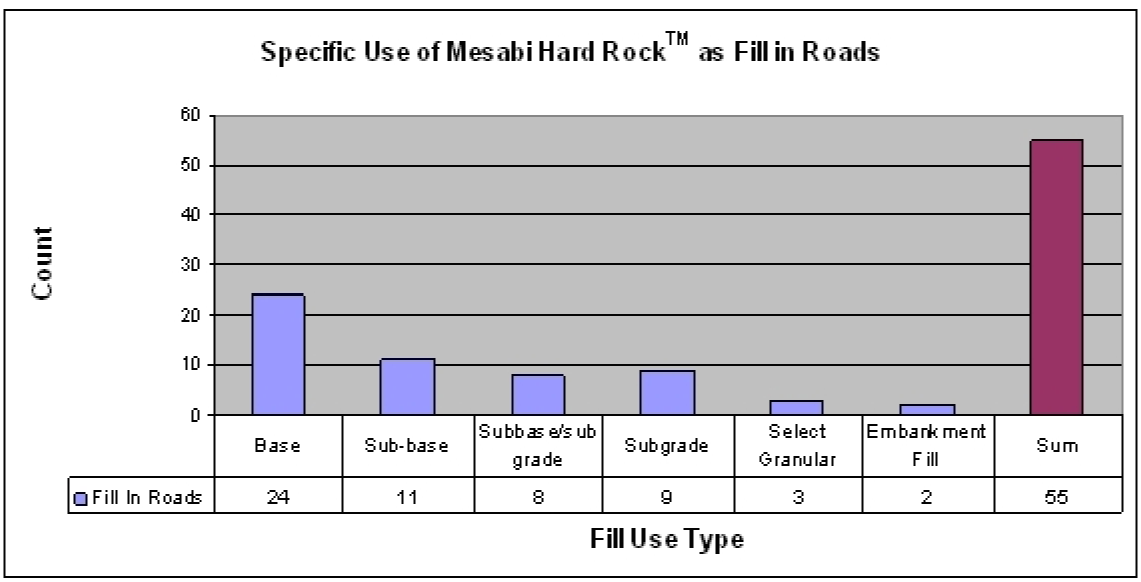

FIGURE 6 Specific uses of Mesabi Hard Rock™ in road fill.

The photo in Figure 7 shows Mesabi Hard Rock™ used as Class 5 on the 6th Avenue reconstruction project in Virginia. This project, done in 2006, used 2 to 6 feet of coarse taconite tailings as common or select borrow and 24 inches of ¾-inch coarse crushed taconite as Class 3 and Class 5 (Hennis, B., 2007, pers. comm.).

FIGURE 7 Mesabi Hard Rock™ Class 5 used on 6th Ave. in Virginia, 2006. Photo by M. Meinders Patelke.

Mesabi Hard Rock™ as Embankment Fill

As shown in Figure 6, embankment fill lists only two occurrences in the database, but one of these two occurrences accounts for nearly 1.82 million tons of coarse taconite tailings! To give the reader an appreciation of what that looks like, a photograph from the construction of the US TH53 / MN TH169 interchange north of Virginia in 2004 and 2005 is included as Figure 8.

Coarse taconite tailings are an ideal fill and embankment material as their low 200-minus content and interlocking angular shape makes for strong, free-draining set-up. They generally meet the specification for select granular. Coarse tailings are placed with water to produce a lock-tight structure. However, they must be capped with 3 inches of Class 5 as the top few inches tend to fluff up and become sugary as moisture is lost (Hill, D. M., pers. comm., 2002).

FIGURE 8 US TH53 / MN TH169 interchange construction north of Virginia. Photo by K. Adolfs.

To really appreciate the value of coarse taconite tailings as embankment fill, one need only look to the dams constructed for the tailings basins at each taconite operation on the Mesabi Range. Coarse tailings have a high friction angle and lock tight. There is little slope failure. The slopes silt in (lifts are covered with clay at Hibbing Taconite, for example) with the fines migrating down to plug up pore spaces to prevent leakage. Some of these dams are 200- to 300-feet high (Wilkins, E., 2006 meeting notes).

Large volumes of coarse taconite tailings, as above, have generally been used only in close proximity to the taconite mines for fill and embankment purposes. This is changing, however. Trainloads of tailings were hauled to Duluth for the Piedmont Ave. (US TH53) reconstruction project in 2004 and 2005. They were used both in the roadbed and as geotechnical fill behind high retaining walls.

Highway "Usage Miles" of Mesabi Hard Rock Use

From project specification books and plotting project start and stop points in ArcView, "usage miles" were obtained for a significant number of database entries. Usage miles are defined as the number of miles a given application (i.e., bituminous pavement, fill, drainage, etc.) was used on a project. If Mesabi Hard Rock™ was used for more than one application on any given project, the total usage miles would reflect the sum of usage miles for the individual applications. Thus, the project usage miles could be, in certain cases, 2 or 3 times the actual project length.

As seen in Figure 9, the total usage miles of Mesabi Hardrock™ use, where determined, is 1,120 miles. Broken down by application, this comes to 974 miles of bituminous pavement, 124 miles of fill, and 22 miles of drainage (fine filter aggregate). The figures for fill and drainage may be slightly overstated. For example, Mn/DOT reported using coarse taconite tailings as fine filter aggregate on a 14-mile stretch of US TH53 in the Central Lakes area in 1999 (SP 6917-112). The count for drainage assumes that the fine filter aggregate was used for the entire length of the project.

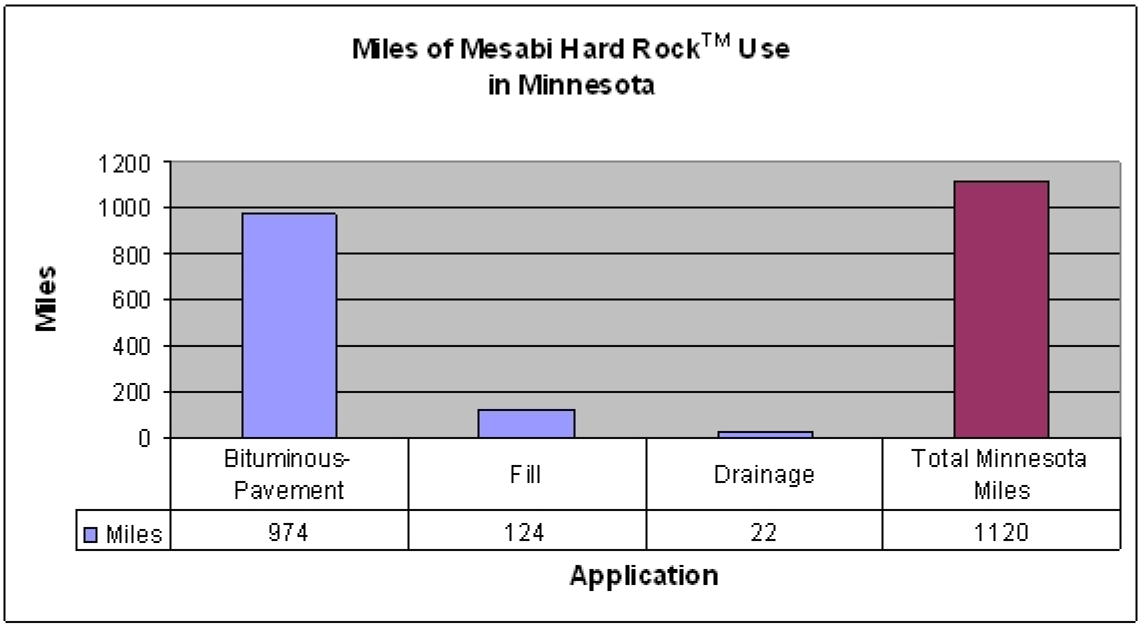

FIGURE 9 Usage miles of Mesabi Hard Rock™ use.

Mesabi Hard Rock™ usage miles for road fill applications can be broken down by type as follows:

- Base 70 miles
- Sub-base 44 miles
- Sub-base/subgrade 3 miles
- Subgrade 6 miles

The figures include both coarse crushed aggregate and coarse taconite tailings. Base and sub-base are the most common uses.

Mesabi Hard Rock™ Use in State, County and Municipal Projects
The greater majority of Mesabi Hard Rock™ usage occurrences documented in this project were by state, county or municipal authority. Project numbers, where available, are included in the database. A total of 105 project numbers were obtained. Project authority breaks down as follows:

- SP (State Project) 80
- SAP (State Aid Project) 10
- MSAP (Municipal State Aid Project) 7
- CP (County Project) 6
- MP (Municipal Project) 2

Over 85 % of the projects were sponsored by Mn/DOT. This may be a reflection of the dominant source of our data.

PROJECT SUMMARY

Changing times and economics have altered the perception of what was once termed "waste" in the taconite mining industry. "Waste" has become a premier aggregate resource. Coarse taconite tailings, together with coarser aggregates produced by crushing pit "wastes," comprise Mesabi Hard Rock™, premium aggregate products bearing the strength and durability of trap rock. Coarse tailings exit the ore concentrating process as a market-ready product. Blast rock and coarse crushed rock, once thought of merely as waste rock to be removed and stockpiled in order to get at the iron ore, now are crushed to specification to produce a premium aggregate.

Mesabi Hard Rock™ has been a staple of the road construction industry on the Mesabi Iron Range in northeastern Minnesota for over four decades, particularly in areas of close proximity to a taconite mining operation. Locally it has been primarily used in road construction as fill and bituminous pavements. Cities such as Duluth, Virginia, Hibbing, Eveleth, and Mountain Iron, as well as Mn/DOT and the local county highway departments, have found these "waste" products to be a valuable resource, particularly the coarse tailings that serve as ready-made fine aggregate equivalent.

Infrastructure for moving Mesabi Hard Rock™ throughout the country is already in place, due to 50 years of shipping taconite pellets. The taconite industry is served by major highways, two major railroads, and ship-loading facilities on Lake Superior at Silver Bay, Taconite Harbor, Two Harbors, and Duluth, Minnesota; and in Superior, Wisconsin. Materials trucked or railed to the Minneapolis-St. Paul metro area can be loaded onto barges for shipment down the Mississippi River.

This project has built a database and GIS product of locations where Mesabi Hard Rock™ has been used. It is searchable by project number, location, product, application, general or specific use, contact source, and more. Specific notations about a given entry can be found in the remarks column. This database / GIS project can be used by parties interested in Mesabi Hard Rock™ products as a guide to usage locations for visual inspection or further testing by means of coring. It provides references to state, county, and municipal personnel, as well as contractors, engineers, and industry representatives that can address issues related to use of Mesabi Hard Rock™.

As NRRI's Mesabi Hard Rock™ research program continues, more use data will be obtained and added to the existing database and GIS product, and updates will be made available.

ACKNOWLEDGEMENTS

This project is part of a broader taconite aggregate resource study that is being supported by a federal grant from the Department of Commerce, Economic Development Administration with additional support from the Permanent University Trust Fund, Iron Range Resources, Minnesota Power, the Blandin Foundation, and Minnesota Technology, Inc.

Locally, over 100 individuals have contributed to this compilation of the historical use of Mesabi Hard Rock™ taconite byproducts as construction aggregates in the state of Minnesota. Engineers, administrators, technicians and operators, current and retired, from state, county, and municipal governments and government agencies, engineering firms, construction companies, testing laboratories, consulting firms, taconite mining operations, and industry support groups have provided the anecdotal information and hard data contained in the GIS product. We gratefully acknowledge each of these contributors.

Special recognition is due to several retired and current Mn/DOT personnel for providing access to project data. This includes: D. Marvin Hill (former Senior Transportation Specialist), Al Schenck (former head of analytical laboratory), Kevin Adolfs (Resident Engineer), and Ted Sexton (Resident Engineer).

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APPENDIX B: Summary memo of initial portland cement concrete (PCC) testing

By
Lev Khazanovich, Associate Professor,
Department of Civil Engineering, University of Minnesota, Minneapolis

Executive Summary

Included in this memo are the first results of activities related to investigation of potential use of taconites as coarse and fine aggregates in portland cement concrete. The memo presents the results of the taconite sieve analysis and particle shape classification. Workability and flexural strength test results on two different mixes are also provided along with a summary of future tests.

Sieve Analysis

To verify if the taconite that was received by the UMN was sieved correctly, sieving was conducted in the UMN Civil Eng. Lab according to ASTM C136. The results are presented below in *Table B1*. The left column of Table 1 lists the taconite sizes as they were labeled. The top row lists the standard sieve sizes typically used in concrete design. The mass percent retained on each size is shown with the correct size in bold. Many of the aggregate sizes contain a high percentage of smaller particles.

Table B1. Sieve Analysis

	Percent Retained												
	1.5”	**1”**	**¾”**	**½”**	**3/8”**	**#4**	**#8**	**#16**	**#30**	**#50**	**#100**	**#200**	**pan**
-1.5” +1”	7.6	***84.9***	6.6	0.6	0.1	-	-	-	-	-	-	-	0.3
-1” +3/4”	-	15.6	***66.0***	17.8	0.2	-	-	-	-	-	-	-	0.3
-3/4” +1/2”	-	-	-	***65.3***	32.8	1.8	-	-	-	-	-	-	0.1
-1/2” +3/8”	-	-	-	0.7	***47.1***	52.0	-	-	-	-	-	-	0.1
-3/8” +3/16”	-	-	-	-	-	***79.4***	20.3	0.1	-	-	-	-	0.2
-3/16” + #8	-	-	-	-	-	0.5	***72.5***	26.6	0.2	-	-	-	0.3
-#8 +#14	-	-	-	-	-	-	0.1	***86.6***	12.9	-	-	-	0.4
-#14 +#28	-	-	-	-	-	-	-	0.2	***75.9***	21.4	2.2	0.2	0.1
-#28 +#48	-	-	-	-	-	-	-	-	4.2	***88.9***	6.4	0.3	0.2
-#48 +#100	-	-	-	-	-	-	-	-	0.1	3.4	***91.4***	5.0	0.1

Observations: 65-90% corresponded to specified gradations. Sieve sizes used are not the same as typically used in concrete design.

Particle Shape

Particle shapes were measured and classified based on ASTM D 4791. A particle was determined to be flat if its width was greater than 3 times its thickness. A particle was determined to be elongated if its length was greater than 3 times its width. The taconite received had many flat and elongated particles. *Table B2* shows the percent by mass of Flat, Elongated, and Flat and Elongated particles for the coarse aggregate sizes.

Table B2: Percent by mass of Flat, Elongated, and Flat and Elongated particles in CA

Aggregate Size	% Flat	% Elongated	% Flat and Elongated
-1.5" +1"	16.7	4.2	20.9
-1" +3/4"	9.6	0.6	10.2
-3/4" +1/2"	17.4	0.0	17.4
-1/2" +3/8"	15.4	0.2	15.6

According to the Portland Cement Association (PCA) handbook, flat and elongated particles should be limited to no more than 15% by mass of the total aggregate. We have greater than 15% at the 1", ½", and 3/8" sizes. To test the effects that the high percentage of elongated particle would have on strength, two beams were made and tested. Both beams were made of 100% taconite aggregate and used the mix design and aggregate gradation shown in *Table B3* and *Figure B1* below. Both beams were air entrained but their air content was not measured.

Table B3: Beam Mix Design

Summary 1 ft^3 (w/c 0.4)		
Water	1.1	lb
Cement	30.1	lb
CA_{SSD}	73.5	lb
FA_{SSD}	48.5	lb
Dairavair	123	ml
Cement type	III	

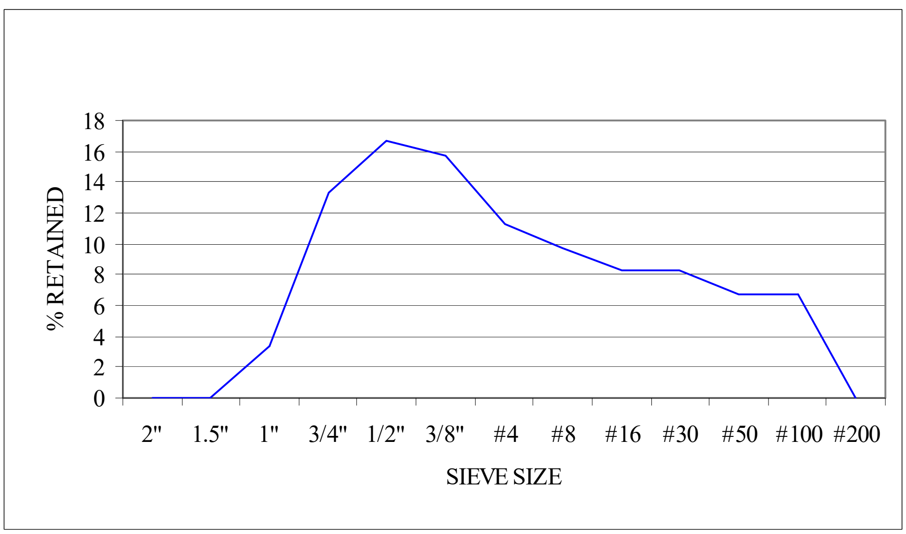

Figure B1: Total aggregate gradation

Beam 1 used aggregate that had 0% flat and elongated particles in the 1”, ¾”, ½”, and 3/8” sizes. The aggregate for this beam was hand picked from the taconite bins. Measurement and sorting took approximately 12 hours. Beam 2 used aggregate that contained flat and elongated particles according to *Table B2*. The aggregate for each beam was washed according to the following procedure:

Aggregate Washing Procedure:

1. Aggregate sizes #8 and larger was washed on the #16 sieve.
2. Aggregate sizes #200 to #16 was washed on the #200 sieve.
3. After washing, aggregates were mixed together and air dried for 60 hours (until the moisture content was around 10%).

The slump of each mix is shown in *Table B4* below. The beams were then cured in a water bath for 28 days. Then at 28 days the flexure strength (MOR) was measured according to ASTM C78.

Table B4: Measured beam properties

	Slump (in.)	Modulus of Rupture (psi)
Beam 1	4.0	672
Beam 2	2.5	964

Observations: Both beams exhibited sufficiently high flexural strength. As expected, the PCC mix with flat and elongated particles had lower workability (lower slump) than the mix without flat and elongated particles. However, surprisingly, Beam 2 (PCC mix with flat and elongated particles) had a MOR that was 43% greater than MOR of Beam 1. It should be noted that only one beam was tested for each aggregate mix, so the results of the strength tests should be taken with caution. Also, ultimately the mixes should be tested for the equal workability conditions. To achieve the same workability, it would be necessary to increase water/cement ratio, which would results in decreased strength.

Recommendations

Washing and sieving the aggregate is very time consuming. Future aggregates that are washed and separated based on typical sieve sizes would be much easier to work with. The taconite that was supplied contains a high percentage of flat and elongated particles. Aggregates with this shape can break easily when working with them and also cause workability problems when used in concrete. It is highly desirable that future aggregates will contain as little flat and elongated particles as possible.

Proposed next activates

To verify the results of the beams test described in this memo, three more beams will be made and tested using 100% taconite (identical to Beam 2). Freeze-thaw tests on beams made using flat and elongated taconite will also be conducted. Mixes incorporating taconite coarse aggregate and normal fine aggregate will also be made and tested for compressive strength, modulus of elasticity, MOR, and freeze-thaw durability.

APPENDIX C: Revised Stratigraphy of the Biwabik Iron Formation, Mesabi Range, Minnesota - Developing the "Rosetta Stone"

By Mark J. Severson and John J. Heine

An electronic version of the poster depicted in Figure C1 is included on CD in the rear pocket.

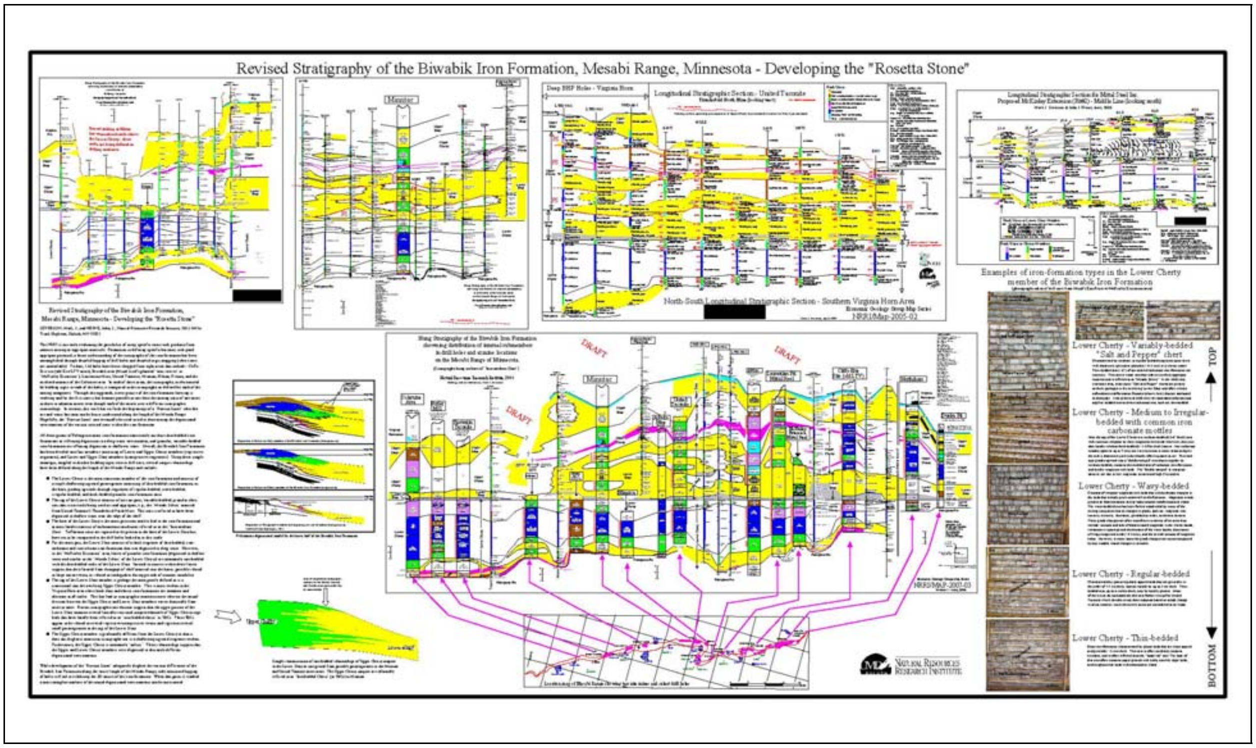

Figure C1. Revised Stratigraphy of the Biwabik Iron Formation, Mesabi Range, Minnesota - Developing the "Rosetta Stone."

APPENDIX D: Sequence Stratigraphy Study of the Biwabik Iron Formation

By Marsha Meinders-Patelke

Can sequence stratigraphy be applied to the Biwabik Formation? The objective of this study is to build a detailed sequence stratigraphic framework using rock core descriptions, outcrop observations and thin section analysis. It is hoped that by applying sequence stratigraphy methods to the Biwabik a predictive model can be developed that will enhance mining methods for Mesabi Hard Rock™ by better defining and anticipating where low silica iron formation and higher silica rocks (good taconite aggregate) will be encountered.

As sediment is deposited it can incorporate signatures that, if preserved, provide clues as to its origin, environment of deposition, response to sea level change, water depth, energy regime, sediment supply, and other conditions. Divisions created by unconformities and flooding surfaces created by changes in sea level are time lines (surfaces) that subdivide the rock record into packages of contemporaneously deposited sediments. Sequence stratigraphy is a method of evaluating sedimentary units that uses time lines to subdivide the rock record into genetically related successions of sedimentary rock layers. The principal that allows sequences stratigraphy to predict the location of specific sedimentary packages is Walther's Law. It states that in an undisturbed vertical sequence of sedimentary rocks, the sedimentary beds that are observed were originally deposited next to each other horizontally.

A simple analogy to describe sequence stratigraphy is to think of the sediment types a person would encounter as they walked across the current sediment surface from Duluth, Minnesota across the bottom of Lake Superior up to the shore of Bayfield, Wisconsin. You would cross bedrock surfaces, glacial deposits, beach sands, lake clays and river sediments. The variety of sediment would be determined by the location and would be indicative of the environment at that location. Over time the site of these types of sediments can shift. For example, if there was a shift in lake level (lake level rises) over time the beach deposits become covered by lake clays, creating a new surface (time line), as shown schematically in Figure D1.

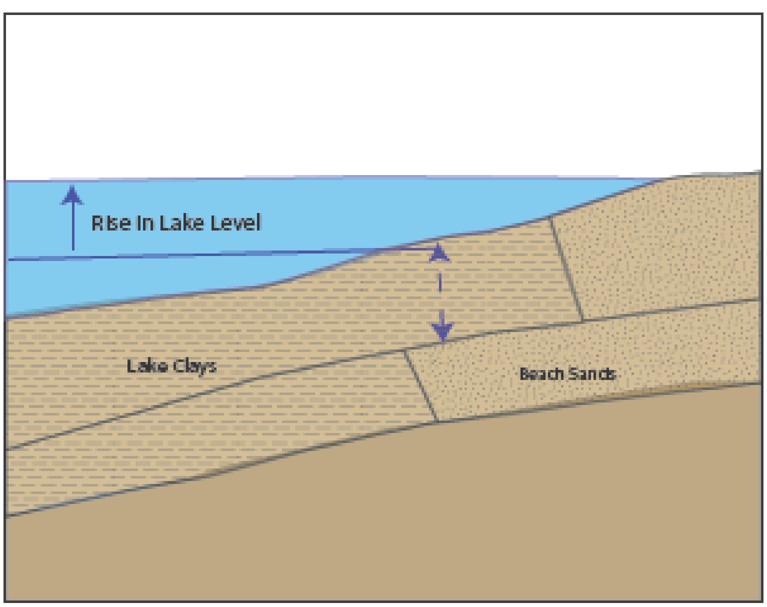

Figure D1. Schematic illustration of sediment deposition.

To begin to build a sequence stratigraphic framework, core from across the range that extends from the Pokegama Quartzite to the Virginia Formation is being logged. Shorter holes will be used later to fill in between the deep holes.   A new logging sheet was developed to record observations regarding composition, texture, grain size, bedding structures, form, fossils, associations and other items. Detailed logging has been completed on approximately1,545 feet of rock core from 5 drill holes for sequence stratigraphic purposes.

In addition, photographs of the core are being taken. These are being compiled into a series of "classic" photographs which depict the various rock types and bedding forms observed in the Biwabik that are used during core logging. This will provide a visual key along with a verbal description for identifying the sequence of rocks associated with Mesabi Hard Rock™.

APPENDIX E: The Tinklenberg Group: Project Reporting

The Tinklenberg Group
The interchange of strategies and solutions

To: Larry Zanko

From: Elwyn Tinklenberg, President, The Tinklenberg Group

Re: November 2006 – March 2007 Progress Report: The Mesabi Hard Rock Project

Date: June 27, 2007

Extensive progress was made throughout the period of November 2006 – March 2007 to advance the Mesabi Hard Rock project. As reported by project consultants, discussions regarding distribution logistics, demonstrations, potential aggregate customers, and project strategy and marketing.

Distribution Logistics
Several conversations occurred with the Port of Milwaukee and Kinder-Morgan terminals regarding rates and using the terminal services for crushed rock. Additionally, multiple phone conversations were held with Krech-Ojard and DM&E regarding ballast specification and use, as well as rail car arrangements and leasing.

Demonstrations and Potential Aggregate Customers
Several emails, phone calls, as well as a group conference call occurred to advance the progress with IDOT and Sheila Beshears regarding the status of the project for the road demonstration, receiving approval for MHR shipments, arrangements with Bluff Cities Materials and securing railroads for transport. Contact was made with M. Vondra to discuss MHR unloading details, and additional contacts were made with Bluff Cities to transmit conveyor photos and specifications, to discuss aggregate unloading issues, to review a sample operating budget for the project and to gather information on equipment specifications for crushers.

TTG consultants also attended a meeting with Progressive Rail in Lakeville, MN to discuss specifications, distribute photos of under-hopper conveyor systems for rock handling and bulk storage, and to discuss equipment contacts in Chicago.

Further, following up on contacts made at the AASHTO convention, TTG consultants collected and forward product information for PolyCarb.

Project Strategy and Marketing
Additionally, TTG consultants provided project updates, logistics information, marketing information, demonstration updates, and strategic plans to NRRI through phone discussions, emails, and a meeting in Duluth. Additional conversations to follow up on mine contacts occurred with F. Ongarro and A. Womsik of the Iron Mining Association.

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The Tinklenberg Group

The interchange of strategies and solutions

To: Larry Zanko

From: Elwyn Tinklenberg, President, The Tinklenberg Group

Re: April 2007 Progress Report: The Mesabi Hard Rock Project

Date: May 8, 2007

Following The Tinklenberg Group's response to an NRRI RFP for continuing logistics and marketing consultant services for the Mesabi Hard Rock Project in February and March, 2007, a new contract award was formalized effective April 1, 2007. A Logistics Project Management Committee meeting was held on April 10, 2007, in Hinckley, MN to update all participating parties on the status of the work. The Tinklenberg Group reported on the ongoing work maintained with Illinois DOT, and the physical and transportation arrangements that had been made involving Laurentian Aggregate, CN, BNSF, EJ&E, and Bluff Cities Materials in Chicago. The current hold on the demonstration in Illinois, due to funding disruptions, was discussed and plans to move ahead with that effort as soon as possible were shared. El Tinklenberg has subsequently been in communication with his senior contacts at IDOT, and is pursuing a possible alternative demonstration site. An effort to transport bulk aggregate to Chicago for crushing, testing, and preparation for future use is being arranged.

American Surface Lines updated the status of their RailMate system, and Tinklenberg Group committed to assist in a possible Mesabi aggregate move on a test basis later in 2007. On another front, Tinklenberg Group has been in contact with Richard Stewart and the Logistics Institute at UW-Superior on their contract to explore and expand on logistics options for water transport of MHR to the lower Great Lakes. Tinklenberg also noted that efforts would be made to enlist aggregate users in the Twin Cities market in the near future to assist in both the RailMate demo and unit train demonstrations. Aggregate Industries and Cemstone continue to express interest in this area.

Other activities during the month included continuing contacts on several fronts. David Christianson had the opportunity to discuss MHR, aggregate needs, and transportation with Frank Ziegler, Director of North Dakota DOT. EMS, a consultant being retained for environmental assessments on the development of the copper-nickel deposits in the Range, contacted Mr. Christianson on logistics issues and information on aggregate and other bulk shipment options in Northern Minnesota. Craig Pagel, the new President of the Iron Mining Association was contacted in April to initiate discussions with IMA members. Mr. Pagel was brought up to speed on the project, the work done previously with Frank Ongaro, his predecessor, and tentative personal meetings with him in early June are being arranged, after his immediate State and Congressional commitments have lessened.

The Tinklenberg Group has re-established contacts with several parties in State and US/DOT offices, and is discussing legislative options that may improve the marketability and applications for MHR. Included in these discussions have been consideration of additional demonstration opportunities and the use of MHR in specialty applications such as hardened and high density concrete. Excess MHR samples have been retrieved from the MnDOT materials lab and are being forwarded for testing in these applications.

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The Tinklenberg Group

The interchange of strategies and solutions

To: Larry Zanko

From: Elwyn Tinklenberg, President, The Tinklenberg Group

Re: May 2007 Progress Report: The Mesabi Hard Rock Project

Date: June 27, 2007

Several connections were made during May 2007 to further advance the Mesabi Hard Rock project. Craig Pagel, new President of the Iron Mining Association, was contacted and briefed on the project. Current status was discussed, and Mr.Pagel agreed to approach the mine owners in the near future to finally make a productive connection for the project. Follow-up calls and meetings have been scheduled for June. Illinois DOT was contacted by both El Tinklenberg and Dave Christianson, to check on demonstration site selection, review progress, and allow for more testing of material from alternative mine sites in preparation for a renewed product shipment for the IDOT demonstration.

The Tinklenberg Group made contact with the Chicago district and aggregate supplier. El Tinklenberg traveled to Washington D.C. to discuss this project with officials, and met with leaders from FHWA and AASHTO, as well as members of the Minnesota congressional delegation, including Congressman Oberstar.

Conference calls with NRRI staff led to a meeting of project partners in Virginia on May 30, 2007, where new marketing leads were discussed, assignments updated, and possible demonstration contacts with MnDOT were established. New uses for various grades of mine tailings were reviewed, and new potential uses and logistics streams were discussed for possible business development.

A tour of Mintac mine and Ulland Brothers was arranged for the afternoon of May 30. Additionally, a meeting was held with U.S. Steel plant management to discuss prospects for use of their aggregate and tailings. They initiated a very detailed conversation on the transportation and material supply economics to determine whether they should offer support to the study, and were apparently satisfied with the answers that the project group supplied. They offered limited free assistance to facilitate taconite supplies for Coleraine for crushing and testing, and remain open to greater participation. The group toured the mine, particularly the area and geologic strata that was being mined to supply the crushed rock for Ulland Bros. ballast. The rock crushing, cleaning, and grading operation at the railhead was viewed at the Ulland Bros. site prior to returning to the U.S. Steel offices at Mountain Iron.

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The Tinklenberg Group

The interchange of strategies and solutions

To: Larry Zanko

From: Elwyn Tinklenberg, President, The Tinklenberg Group

Re: June 2007 Progress Report: The Mesabi Hard Rock Project

Date: July 3, 2007

In June 2007, The Tinklenberg Group staff continued work on advocating at the congressional level on behalf of the Mesabi Hard Rock project providing congressional updates, coordination with Congressman Oberstar's office, and attending meetings in Washington D.C. Elwyn Tinklenberg traveled to Washington, D.C. for the MN Transportation Alliance Fly-In and met with several key leaders about the project, including Congressman Jim Oberstar and Bill Richard, who continue to be supportive of the efforts. Additionally, Elwyn met with Jason Tai from Congressman Lipinski's office to discuss work with the Illinois Department of Transportation. Congressman Lipinski continues to be supportive of the concept of the Illinois DOT using Iron Range aggregate. While Illinois is having a difficult legislative session, IDOT has indicated to Elwyn that they are still interested in doing something this year using Iron Range aggregate in a demonstration project.

Consultants at The Tinklenberg Group continue to explore additional avenues and markets for the Iron Range aggregate, and have met with James Peak at the Army Corps of Engineers, whose staff is exploring the possibility of testing the aggregate to determine the potential use in projects. Additionally, staff from The Tinklenberg Group has been meeting with contractors, construction companies, aggregate users and others who are considering using the product in a major demonstration project in the Twin Cities metro area.

Finally, staff at The Tinklenberg Group have been in discussions with BNSF, and have been exploring unit train options along the BNSF track for successful movement of the aggregate.