Alkali Silica Reactivity Testing of Four Taconite Ledges for Potential Use as Aggregate Concrete

Minnesota Department of Transportation

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16. Abstract (Limit: 250 words)

This report includes the test results on aggregates from four taconite strata from the Mesabi iron range of Minnesota for concrete qualities including Los Angeles Rattler (LAR), absorption, flatness and elongation, magnesium sulfate, ASTM C 1260, and ASTM C 1293. The strata are identified as LC-8 Bed from United Taconite, LC-5 Bed from Ispat Inland/Mittal Steel (Laurentian Pit), LS-2 Bed from Ispat Inland/Mittal Steel (Laurentian Pit), and LUC Bed from United Taconite. A granite source, known to have moderately low expansion characteristics was also tested for comparison.

All ledges tested well for Los Angeles Rattler and magnesium sulfate soundness. Ledges LS-2, LC-8, and LS-2 had excellent results for ASTM C 1260 and ASTM C 1293 expansion, while the LC-5 ledge performed very poorly. The Coal Creek fly ash used in the ASTM C 1293 tests mitigated ASR expansions much better than the slag mixes. As with any natural aggregate source, the physical and chemical properties of the taconite ledges vary. Because of the high variation in expansion potential, each potential concrete strata should be tested within a mine using ASTM C 1293. A Quality Control plan should be developed for each source. Specific gravity may be used to screen out potential deleterious strata, and should be performed frequently, perhaps on each blast. ASTM C 1260 tests should also be used on a frequent basis.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

This report includes the test results on aggregates from four taconite strata, from the Mesabi iron range of Minnesota, for concrete qualities including Los Angeles Rattler (LAR), absorption, flatness and elongation, magnesium sulfate, potential alkali reactivity of aggregates (mortar-bar method [ASTM C 1260]), and length change of concrete due to alkali-silica reaction (ASTM C 1293). The strata are identified as the LC-8 Bed from United Taconite, LC-5 Bed from Ispat Inland/Mittal Steel (Laurentian Pit), LS-2 Bed from Ispat Inland/Mittal Steel (Laurentian Pit), and LUC Bed from United Taconite. A granite source, known to have moderately low expansion characteristics was also tested for comparison.

All strata had passing results for LAR, flatness and elongation, and magnesium sulfate. Each stratum was tested in accordance to ASTM C 1293 and ASTM C 1260. Three mixes for each aggregate source were prepared for the ASTM C 1293 and ASTM C 1260 tests, one with cement only, one with cement and 30% fly ash (Coal Creek), and one with cement and 35% Ground Granulated Blast Furnace Slag (GGBFS).

The LC-5 failed the cement only and cement with slag mixes. A lithological analysis showed that LC-5 has very high magnetite and silica contents. The high magnetite content was reflected in its high specific gravity of 3.304. Additionally, the high silica content likely contributed to its failure in the ASTM C 1260 and the ASTM C 1293 tests. Two additional tests, using cement only, were performed on the LC-5 strata, these also failed.

LS-2 had a very low magnetite rich percentage and a relatively average siliceous percentage and performed well in the ASTM C 1260 and ASTM C 1293 tests.

LC-8 had a moderately high magnetite rich content and an average to moderately high siliceous percentage and performed very well in the ASTM C 1260 and ASTM C 1293 tests.

LUC had moderately high magnetite content and a moderately low siliceous percentage and performed marginally in the ASTM C 1260 tests, but well in the ASTM C 1293 tests.

The granite source performed well in the cement only test, and had borderline results with the slag mix.

All four of the taconite aggregates performed well when a 30% replacement of cement with fly ash was used.

CHAPTER 1 – BACKGROUND AND PURPOSE

The Natural Resources Research Institute (NRRI) is investigating the potential use of taconite waste rock for use in building materials. This waste rock comes from two sources: waste ledges, which are composed of rock with low recoverable iron content and are removed to expose the iron rich taconite, and coarse tailings, which come from rock crushed down for taconite pellet production. Minnesota taconite mines produce approximately 60 million tons of waste rock/year, of which about 60% is from waste ledges and 40% is from coarse tailings. To put these numbers in perspective, the state of Minnesota uses approximately 55 million tons of aggregate/year for concrete, base, and bituminous. Therefore, there is great potential use for this rock for base materials, bituminous mixes, and for concrete coarse aggregate.

Many times in the past, Mn/DOT has used waste taconite rock as a base material and in bituminous pavement. However, except for a recent experimental test section at the Mn/ROAD research site, taconite has not been used in concrete on any other Mn/DOT projects.

A mineralogical analysis revealed that microcrystalline silica is present throughout much of the iron formations. Microcrystalline silica within aggregates has the potential to react with cementitious materials and cause a premature failure of concrete. Because of this, Mn/DOT is concerned that taconite aggregate may cause concrete failure. The NRRI requested that selected ledges of taconite, which may have the potential to be used in concrete, should be tested for alkali silica reactivity according to ASTM C 1293, Standard Test Method for Determination of Length Change of Concrete Due to Alkali Silica Reaction and ASTM C 1260, Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method).

The purpose of performing these laboratory tests was to evaluate specific taconite strata for use in concrete. Because of the presence of microcrystalline silica within taconite, Mn/DOT is concerned that taconite has the potential for alkali silica reaction (ASR). Positive tests results, especially for the ASTM C 1293 tests, should alleviate most concerns for these specific strata. Mn/DOT is testing three mixes per sample ledge to assess the use of waste taconite rock in concrete.

The four ledges were:

1. LC-8 Bed (111-05) from United Taconite
2. LC-5 Bed (111-05) from Ispat Inland/Mittal Steel (Laurentian Pit)
3. LS-2 Bed (100-05) from Ispat Inland/Mittal Steel (Laurentian Pit)
4. LUC Bed (114-05) from United Taconite

ASTM C 1293 testing was also performed on Meridian Granite from Saint Cloud as a comparison coarse aggregate. This granite has a low to moderate history of expansion in the ASTM C 1293 test and no known history of deleterious expansion in the field.

Tests for the Four-Taconite Rock Ledges

As part of the ASR tests, Mn/DOT conducted a variety of preliminary tests to provide information either needed for the ASR testing or to better define the characteristics of taconite waste products. These tests included:

1. Specific gravity
2. Absorption

3. Oven-dry-rodded unit volume
4. Los Angeles Rattler (LAR)
5. Magnesium sulfate soundness
6. Flat and elongation analysis
7. Lithological analysis
8. ASTM C 1293 Tests: One test used cement only, one cement with 30% type F fly ash (Coal Creek), and one cement with 35% Holcim Grancem GGBFS. Readings were taken at the following intervals: 1 day (initial), 7 days, 1 month, 2 months, 3 months, 6 months, 12 months, 18 months and 2 years.
9. Two ASTM C 1260 tests were performed per ledge on the crushed taconite using Holcim cement and Davenport Lafarge cement.

Tests on Cement, Fly Ash, and Slag

Mn/DOT performed testing on the cement, fly ash, and slag used for the ASTM C 1293 tests.

A. Cement meeting the requirements of ASTM C 1293 was to be used for each mix. Tests included:

    1. Vicat
    2. Gillmore
    3. Autoclave expansion
    4. Compressive strength
    5. Air content
    6. Blaine fineness
    7. 325 fineness
    8. Specific gravity test
    9. Chemical analysis

B. Coal Creek, a fly ash that has many characteristics of a type F fly ash, was used for the concrete with fly ash. Mn/DOT performed the following tests on the fly ash:

    1. Autoclave expansion
    2. Compressive strength
    3. 325 fineness test
    4. Specific gravity test
    5. Chemical analysis

C. Mn/DOT performed the following tests on the slag used for the concrete.

    1. Autoclave expansion
    2. Compressive strength
    3. 325 fineness test
    4. Specific gravity test
    5. Chemical analysis

Tests on Sand Used in ASTM C 1293 Tests

Mn/DOT used CanMET sand, standard sand used for ASTM C 1293. Tests included:

1. Specific gravity
2. Absorption
3. Gradation
4. Color plate
5. Lightweight pieces in aggregate
6. Two ASTM C 1260 tests on this standard sand using Holcim and Davenport Lafarge cement

Tests on Concrete

1. One concrete slump test (ASTM C 143) for each mix, three per source
2. One Air Test (ASTM C 231) for each mix, three per source
3. Two 28-day Compression strength tests (ASTM C 39) from for each concrete mix, three per source
4. One moisture determination test of the sand (AASHTO T 255), and one on each of the three coarse fractions (AASHTO T 255) for each mix
5. One concrete beam flexural test (AASHTO T 97) broken at 28 days. An additional beam was made and broken at 7 days for all mixes except the LC-8 ledge
6. One unit weight test (ASTM C 138) of concrete per mix

CHAPTER 2 – TEST RESULTS

Coarse Aggregate Properties

Aggregate qualities were performed on each of the coarse aggregate and are presented in Appendix A. Tests included: specific gravity, absorption, Los Angeles Rattler (LAR), Magnesium Sulfate ($MgSO_4$), oven dry rodded unit weight, flat & elongated - concrete specification, and flat & elongated - bituminous specification.

- The LAR, $MgSO_4$, flat & elongated - concrete specification, are quality tests which aggregates must meet to be used in concrete. All of the coarse aggregates met the specification for these tests.
- The flat & elongated - bituminous specification test was run on each sample to determine whether the aggregates would meet this specification. All of the coarse aggregates met that specification.
- The specific gravity, absorption, and oven dry rodded unit weight tests were perform for mix design purposes. There is no specification on these tests.

Preliminary Testing for ASTM C 1293

Preliminary tests were performed on the fine aggregate, cement, fly ash, and slag. These are presented in Appendix B. All tests met requirements for ASTM C 1293.

ASTM C 1293 Concrete Mix Design, Expansions, and Concrete Properties

ASTM C 1293 concrete mix design data, expansions, and concrete properties are presented in Appendix C. Data include:

1. Dry rodded unit weight of coarse aggregate
2. Moisture content of fine aggregate
3. Moisture content of coarse aggregate
4. Concrete slump
5. Air content of concrete
6. Concrete temperature
7. Room temperature
8. Date and time of mix
9. Unit weight of concrete
10. Water/cement ratio
11. 28-day concrete cylinder compression strength tests
12. Flexural beam test at 28 and in most cases 7 days (The 7-day beam test was not required; however it was performed for all beams except the LC-8 mixes.)
13. ASTM C 1293 Results - Average Expansion of Four Beams

According to Smaoui, Bérubé, Fournier, and Bissonnette, beams that have been vibrated, will have a lower expansion than beams that are rodded. All of the prism beams in this study were vibrated for uniformity.

ASTM C 1293 Graphic Results

Graphs of the ASTM C 1293 tests are in Appendix D. Included in these graphs are the failure criteria of 0.04%. All beams with the exception of LC-5 performed well. LC-5 preformed very poorly for the cement only and slag mixes. The failure criterion of 0.04% expansion, is based on one-year results for mixes with cement only, and for two years results for mixes with cement and fly ash, or mixes with cement and slag.

The LUC, LC-8, and LS-2 mixes passed both the one-year criteria for the cement only mixes, and the two-year results for the fly ash and slag mixes. The LC-5 mix with cement only and the LC-5 mix with cement and slag both failed, while the LC-5 mix with fly ash passed.

Mn/DOT performed additional ASTM C 1293 testing on the LC-5 strata using cement only. All concrete came from one additional mix. Half of the prism beams were rodded and the other half was vibrated. The original mix was vibrated. These tests have also failed and the results show that the vibrated mix had lower expansions as per the study by Smaoui *et al.*

The granite mixes passed the ASTM C 1293 tests, but had higher expansions than the LUC, LC-8, and LS-2 mixes. The granite slag mix result at two years was at the expansion limit of 0.04%

Also of note is the lower expansion of the beams with fly ash in relation with the cement only mixes or the mixes with slag. Even the LC-5 mix with fly ash passed at two years when fly ash was used.

ASTM C 1260 Results

ASTM C 1260 tests are presented in Appendix E. Tests were performed on crushed samples of LUC, LC-8, LS-2, and LC-5, as well as the natural sand used in the ASTM C 1293 tests. Mn/DOT does not allow crushed sand to be used as a fine aggregate in concrete, because it drives up water demand, which is detrimental to concrete longevity. However, this test is an indicator of whether the ASTM C 1293 test will pass and it takes only two and one half weeks to complete as opposed to the one to two years required for the ASTM C1293 test.

Mn/DOT's ASTM C 1260 failure criteria for a natural sand based on the expansion at fourteen days is the following: "the higher expansion result of two cement and sand combinations shall determine what mitigation may be necessary." If the proposed fine aggregate results are:

≤ 0.150%	The fine aggregate is acceptable with or without a mitigator in the concrete mix.
0.151 - 0.250%	The fine aggregate shall be mitigated with 35% ground granulated blast furnace slag or a minimum of 20% fly ash.
0.251 - 0.300%	The fine aggregate shall be mitigated with 35% ground granulated blast furnace slag or 30% fly ash meeting Mn/DOT Spec 3115 modified with a minimum $SiO_2 + Fe_2O_3 + Al_2O_3$ of 66.0% on a dry weight basis and a minimum SiO_2 content of 38.0%.
> 0.300%	The fine aggregate is rejected.

- As measured by this criterion, the LC-8 sand performed very well with 0.0363% and 0.0440% expansions on two beams and did not require a mitigator.

- The LS-2 also performed well with 0.1087% and 0.1070% expansion and also did not require a mitigator.

- The LUC had expansions of 0.1891% and 0.1693% and required a mitigation with 35% ground granulated blast furnace slag or a minimum of 20% fly ash.

- The LC-5 had expansions of 0.3957% and 0.3730%, which correlates well with its ASTM C 1293 failures. The fine aggregate shall be mitigated with 35% ground granulated blast furnace slag or 30% fly ash meeting Mn/DOT Spec 3115 modified with a minimum $SiO_2 + Fe_2O_3 + Al_2O_3$ of 66.0% on a dry weight basis and a minimum SiO_2 content of 38.0%.

- The sand used for the prism test performed well at 0.0507% expansion, and did not require the use of a mitigator.

Slump, Air Content, Water/Cement Ratio, and Concrete Mix Data

Slump, air content, w/c ratio, and concrete strength data are listed in Appendix C. The major intent of this study was to evaluate taconite for ASR expansion; therefore the requirements of ASTM C 1293 were followed exactly. This made for variations in slump, air content, and w/c ratio, which are not allowed in a normal Mn/DOT pavement mixes. Strength data was adequate to excellent; however, normal mix designs were not used.

Slump

Slumps varied widely from a normal 1 - 2" paving mix, especially for mixes with fly ash. The higher slumps would tend to lower concrete strength, as water would have been lowered in an actual mix lowering the w/c ratio.

- The slumps for cement only mixes were 1.25", 1.75", 3.75" and 2.5" for the LC5, LC8, LUC, and LS-2 mixes respectively.

- The slumps for cement and slag mixes were 3", 1.75", 3.75" and 3" for the LC5, LC8, LUC, and LS-2 mixes respectively.

- The slumps for cement and slag mixes were 7.75", 6.5", 6.5" and 5.5" for the LC5, LC8, LUC, and LS-2 mixes respectively.

Air Content

Air content was less than the normal 6.5% paving mix, because no air admixture was added to the concrete. These lower air contents would tend to increase concrete strength when compared to a normal pavement mix.

- The air content for cement only mixes were 0.8%, 1.6%, 2.1%, and 1.0% for the LC5, LC8, LUC, and LS-2 mixes respectively.

- The air content for cement and slag mixes were 1.4%, 0.3%, 1.9%, and 1.1% for the LC5, LC8, LUC, and LS-2 mixes respectively.

- The air content for cement and fly ash mixes were 1.7%, 0.8%, 2.2%, and 2.4% for the LC5, LC8, LUC, and LS-2 mixes respectively.

W/CM Ratio
The w/cm ratio for each mix was 0.435 (ASTM C 1293 requires 0.42 to 0.45). Normal paving concrete w/cm ratios are under 0.40, and usually vary from 0.35 to 0.38. These higher w/cm ratios would tend to decrease concrete strength.

Concrete Strength
28-day flexural and 28-day compression tests were performed on each mix. As stated earlier, the low air content and higher water cement ratio of these mixes had an effect on concrete strength.

- For the cement only mixes, the 28-day flexural results were 1000+, 960, 930, and 960 psi for the LC5, LC8, LUC, and LS-2 mixes respectively.

- For the cement and slag mixes, the 28-day flexural results were 1000+, 1000+, 1000+, and 905 psi for the LC5, LC8, LUC, and LS-2 mixes respectively.

- For the cement and fly ash mixes, the 28-day flexural results were 920, 825, 845, and 860 psi for the LC5, LC8, LUC, and LS-2 mixes respectively.

- For the cement only mixes, the 28-day compression average results were 6884, 6466, 6290, and 6290 psi for the LC5, LC8, LUC, and LS-2 mixes respectively.

- For the cement and slag mixes, the 28-day compression average results were 6072, 6780, 5908, and 5837 psi for the LC5, LC8, LUC, and LS-2 mixes respectively.

- For the cement and fly ash mixes, the 28-day compression average results were 5288, 5602, 5376, and 5463 psi for the LC5, LC8, LUC, and LS-2 mixes respectively.

Lithological Summary
A lithological analysis performed is presented in Appendix F and includes tables for each of the taconite strata. Appendix F also contains a mineralogical analysis of the taconite ledges.

- LC-5 had a total siliceous percentage of 99.1%, and 70.9% of its aggregate was magnetite-rich which was reflected in LC-5's high specific gravity of 3.304. Its high magnetic percentage would also make it likely to be crushed for iron pellets. This stratum failed both the ASTM C 1260 and ASTM C 1293 tests.

- LC-8 has a total siliceous percentage of 68.6% and a total CO_3 rich percentage of 31.4%. 26.2% of its aggregate is magnetite rich. Its specific gravity was 3.089.

- LS-2 has a total siliceous percentage of 60.8% and a total CO_3 rich percentage of 39.2%. 2.1% of its aggregate is magnetite rich. Its low magnetite percentage is reflected in its lower specific gravity, which was 2.868.

- LUC had a total siliceous percentage of 46.5% and a total CO_3 rich percentage of 53.5%. 34.0% of its aggregate was magnetite rich. Its specific gravity was 3.117.

CHAPTER 3 - CONCLUSION

Waste taconite ledges have the potential of being used for concrete aggregate. All ledges tested well for Los Angeles Rattler and magnesium sulfate soundness. Ledges LS-2, LC-8, and LS-2 had excellent results for ASTM C 1260 and ASTM C 1293 expansion, while the LC-5 ledge performed very poorly.

The Coal Creek fly ash used in the ASTM C 1293 tests mitigated ASR expansions much better than the slag mixes. It was even able to mitigate expansions of the most deleterious aggregate, LC-5. It is recommended that a Type F fly ash, or proximate Type F fly ash be specified in lieu of a slag, or there should be an incentive of fly ash over slag, for strata with a slight to medium potential for ASR expansion. Even though expansion was mitigated by the fly ash, it is recommended that the LC-5 layer or other strata with similar specific gravity, ASTM C 1260, and ASTM C 1293 results be excluded from use in concrete.

As with any natural aggregate source, the physical and chemical properties of the taconite ledges vary. Because of the high variation in expansion potential each potential concrete strata should be tested within a mine using ASTM C 1293. A Quality Control plan should be developed for each source. Specific gravity may be used to screen out potential deleterious strata, and should be performed frequently, perhaps on each blast. ASTM C 1260 tests should also be used on a frequent basis.

REFERENCES

Smaoui, Bérubé, Fournier, and Bissonnette, “Influence of Specimen Geometry, Orientation of Casting Plane, and Mode of Concrete Consolidation on Expansion Due to ASR" *Journal of Cement, Concrete and Aggregates*, Vol. 26, No. 2, December 2004.

APPENDIX A - COARSE AGGREGATE PROPERTIES AND QUALITIES

Table A1. Coarse Aggregate Properties

Test	LC-5	LS-2	LC-8	LUC	Meridian Granite
Specific Gravity	3.304	2.868	3.089	3.117	2.634
Absorption	0.54%	1.80%	1.23%	1.07%	0.74%
LAR, Spec Max = 40%	14%	17%	17%	16%	20%
$MgSO_4$, Spec Max = 15%	0%	4%	2%	2%	0%
Oven Dry Rodded Unit Weight (lbs/ft^3)	107.7	92.0	100.1	101.9	95.4
Flat & Elongation Concrete Spec Max = 15%	1%	3%	6%	1.7%	0%
Flat & Elongation Bituminous Spec Max = 10%	1%	1.3%	6%	1.4%	0%

APPENDIX B - BACKGROUND PROPERTIES REQUIRED FOR ASTM C 1293 TESTS

Table B1. Fine Aggregate Properties

	CANMET Sand
Specific Gravity	2.693
Absorption %	0.40
% Passing #4, Spec 95 - 100 Gradation (AASHTO T 27 - Mn/DOT modified)	100
% Passing #8, Spec 80 - 100 Gradation (AASHTO T 27 - Mn/DOT modified)	95
% Passing #10 Gradation (AASHTO T 27 - Mn/DOT modified)	93
% Passing #16, Spec 55 - 85 Gradation (AASHTO T 27 - Mn/DOT modified)	83
% Passing #30, Spec 30 - 60 Gradation (AASHTO T 27 - Mn/DOT modified)	54
% Passing #40 Gradation (AASHTO T 27 - Mn/DOT modified)	37
% Passing #50, Spec 5 - 30 Gradation (AASHTO T 27 - Mn/DOT modified)	21
% Passing #100, Spec 0 – 10 Gradation (AASHTO T 27 - Mn/DOT modified)	7
% Passing #200, Spec 0 - 2.5 Gradation (AASHTO T 27 - Mn/DOT modified)	2.2
Color Plate (AASHTO T 21)	Lighter than standard Pass
Lightweight pieces in aggregate (AASHTO T 113 - Mn/DOT modified), % Spec 0.0 - 2.5	0

Cement used was Saint Lawrence Cement Type I Boat 9 Duluth Boat loaded 10/16/2005 Mississauga Plant, Company Testing was performed by Holcim - Report Date 11/18, 2005 by James P Johnson.

Table B2. Cement Testing

Test	Mn/DOT Test	Holcim Test
Vicat (AASHTO T 131) Initial Time of Set Spec. 45 minutes Min.	105 & 110	
Vicat (AASHTO T 131) Final Time of Set Spec 375 Minutes Max.	190 & 190	
Gillmore (AASHTO T 154) Initial Time of Set Spec. 60 minutes Min.	170 & 175	
Gillmore (AASHTO T 154) Final Time of Set Spec. 300 Minutes Max.	300 & 290	
Autoclave expansion (AASHTO T 107) Spec 0.80% Max	0.01 & 0.01%	0.03%
1 Day Compressive strength, psi (AASHTO T 106)		2498
3 Day Compressive strength, psi (AASHTO T 106), Spec. 1800 psi Min	3752 & 3818	4126
7 Day Compressive strength, psi (AASHTO T 106), Spec. 2800 psi Min	4565 & 4632	4834
28 Day Compressive strength, psi (AASHTO T 106)		5865
Air content (AASHTO T 137) Spec 12% Max	8.4 & 8.5%	7.9%
Blaine fineness (AASHTO T 153) Spec 3250 to 4200 cm^2/gm	4291, 4306, & 4213	4100
325 fineness test (AASHTO T 192)	5.1%	10.90%
Specific gravity test (AASHTO T 133)	3.1496	
Chemical analysis (ASTM C 114) SO_3 Spec Max 3.00%	4.17 & 4.15%	4.26%
Chemical analysis (ASTM C 114) MgO Spec Max 6.00%	3.35 & 3.39%,	2.52%
Chemical analysis (ASTM C 114) CaO	61.44 & 61.35%	62.33%
Chemical analysis (ASTM C 114) SiO_2	19.89 & 19.72%	19.40%
Chemical analysis (ASTM C 114) Fe_2O_3	2.56 & 2.56%	2.50%
Chemical analysis (ASTM C 114) Al_2O_3	5.10 & 5.01%	5.50%
Chemical analysis (ASTM C 114) NA_2O	0.25 & 0.26%	

Table B2. Cement Testing (Cont.)

Test	Mn/DOT Test	Holcim Test
Chemical analysis (ASTM C 114) K_2O	1.06 & 0.65%	
Chemical analysis (ASTM C 114) C_3A	9.18 & 8.94%	10.35%
Chemical analysis (ASTM C 114) C_3S	49.14 & 50.73%	46.02%
Chemical analysis (ASTM C 114) C_2S	19.95 & 18.27%	20.91%
Chemical analysis (ASTM C 114) C_4AF	7.79 & 7.79%	7.61%
Chemical analysis (ASTM C 114) Insoluble Residue Spec 0.75% Max	0.51 & 0.54%	0.54%
Chemical analysis (ASTM C 114) Loss on Ignition Spec 3.00 % Max	2.14 & 2.19%	2.00%
Chemical analysis (ASTM C 114) Available Alkali	0.95 & 0.69%	0.93%
Chemical analysis (ASTM C 114) Free Lime		1.09%
Chemical analysis (ASTM C 114) CO_2		1.5%
Chemical analysis (ASTM C 114) Limestone		3.7%
Chemical analysis (ASTM C 114) $CaCO_3$ in Limestone		89.3%
Chemical analysis (ASTM C 114) Residue 45 mm		10.9%

Coal Creek fly ash was used, Company Testing was performed by Headwaters Resources, The type of sample was 3200-ton rail, report date 11/2/2005, MTRF I.D. 1771CC.

Table B3. Fly Ash Properties

Test	Mn/DOT Tests	Headwaters Resources Tests
Autoclave Expansion (AASHTO T107), Spec 0.80% Max	0.03%,	0.05%
7 Day Compressive strength AASHTO T 106, Spec 75%+	94%	105%
28 Day Compressive strength AASHTO T 106		105%
325 Fineness Test (AASHTO T 192), Spec 30% Max	24.5%	23.29%
Specific gravity test (AASHTO T 133), Spec 2.50 +/- 0.12	2.50	2.56
Chemical analysis (ASTM C 311) SiO_2	54.20%	50.25%
Chemical analysis (ASTM C 311) Al_2O_3	17.90%	14.95%
Chemical analysis (ASTM C 311) Fe_2O_3	5.20%	6.06%
Chemical analysis (ASTM C 311) Sum of SiO_2, Al_2O_3, &Fe_2O_3 Spec 50% min. class C, 70% min class F	77.3%	71.26%
Chemical analysis (ASTM C 311) CaO, Spec. Max. 40%	10.7%,	16.11%
Chemical analysis (ASTM C 311) MgO	4.70%	
Chemical analysis (ASTM C 311) SO_3 Spec. Max. 5.0% Class C & F	2.32%,	1.03%
Chemical analysis (ASTM C 311) NA_2O	0.40%	
Chemical analysis (ASTM C 311) K_2O	0.40%	
Chemical analysis (ASTM C 311) Available Alkali, Spec Max. 3.0%	0.6%	1.16%
Chemical analysis (ASTM C 311) Loss on Ignition, Spec. Max. 3.0%	0.1%	0.07%
Chemical analysis (ASTM C 311) Moisture content, Spec Max 3.0%		0.07%
Chemical analysis (ASTM C 311) Water requirement % Control, Spec Max 105%		94%

Slag used was Ground Granulated Blast Furnace Slag from Holcim Type 100 (ASTM C 989), Date Range 9/1-30/ 2005, Lot number: multiple lots.

Table B4. Slag Properties

Test	Mn/DOT	Holcim Results
7 Day activity index Meets specs for Grade 100	95	88
28 Day activity index Meets specs for Grade 100	120	109
7 Day Standard compression strength, psi	3687	3920 (monthly average)
28 Day Standard compression strength, psi	5756	5080 (monthly average)
7 Day Compression strength, psi	3514	3342 (sample lot) 3920 (monthly average)
28 Day Compression strength, psi Spec 5000 psi	6926	5472 (sample lot) 5080 (monthly average)
Air Content, Spec 12% Max	6%	4.12%
Spg	2.962	2.85 (monthly average)
% Retained, Spec 20% Max	2.617	
Blaine	6625	6410
Chemical analysis SO_3 Spec 4.00% Max	0.93%	0.12%
Chemical analysis Sulfide Spec 2.5% Max	1.00%	1.32%
Chemical analysis 325 sieve Spec. 20% Max		1.42
Chemical analysis Total Alkalis as Na_2O Spec 0.60 - 0.90%		0.78% (monthly average)
Chemical analysis C_3S		53.93% (monthly average)
Chemical analysis C_2S		19.44% (monthly average)
Chemical analysis C_3A		7.86% (monthly average)
Chemical analysis C_4AF		8.89% (monthly average)

APPENDIX C - ASTM C 1293 MIX DESIGN DATA

Mix: Meridian Granite with Cement Only

Date of Mix: 7/12/2006
Time of Mix: 12:38 PM
Temperature at Time of Mixing: 74^0 F

Table C1. Meridian Granite with Cement Only Mix Design

	Component	Specific Gravity	Absorption	Mass (kg)	Volume (ft^3)
Coarse Aggregate	Meridian Granite	2.634	0.74%	53.009	0.7110
Fine Aggregate	Cantley	2.693	0.40%	34.238	0.4492
Cement	Saint Lawrence Mississauga	3.15		20.815	0.2335
Water		1		9.055	0.3199
Air (2% assumed)					0.0350
NaOH		2.13		0.085	0.0014
Total Volume					1.7500

Dry Rodded Unit Weight Coarse Aggregate: 95.4 lb/ft^3
Moisture of Fine Aggregate: 3.89%
Moisture of Coarse Aggregate: 2.37%
28-day Compression strength tests (ASTM C 39): 6454 & 6501, avg = 6478 psi
Flexural test (AASHTO T 97) broken at 7 days: 790 psi
Flexural test (AASHTO T 97) broken at 28 days: 915 psi
Slump: 7.25"
Air Content: 1.5%
Unit Weight Concrete: 151.232 (lbs/ft^3)
Water/Cement Ratio: 0.435
Concrete Temperature: 79^0 F

Table C2. Meridian Granite with Cement Only ASTM C 1293 Results

7 Days	28 Days	56 Days	3 Months	6 Months	9 Months	1 Year	1.5 Years	2 Years
-0.0075%	-0.0006%	0.0024%	0.0055%	0.0133%	0.0228%	0.0325%	0.0596%	0.0883%

Mix: Meridian Granite with Cement and Slag

Date of Mix: 7/12/2006
Time of Mix: 1:12 PM
Temperature at Time of Mixing: 74^0 F

Table C3. Meridian Granite with Cement and Slag Mix Design

	Component	Specific Gravity	Absorption	Mass (kg)	Volume (ft^3)
Coarse Aggregate	Meridian Granite	2.634	0.74%	53.009	0.7110
Fine Aggregate	Cantley	2.693	0.40%	33.826	0.4438
Cement	Saint Lawrence Mississauga	3.15		13.530	0.1518
Slag	Holcim Grancem GR-100	2.96		7.285	0.0869
Water		1		9.055	0.3199
Air (2% assumed)					0.0350
NaOH		2.13		0.099	0.0016
Total Volume					1.7500

Dry Rodded Unit Weight Coarse Aggregate: 95.4 lb/ft^3
Moisture of Fine Aggregate: 3.89%
Moisture of Coarse Aggregate: 2.49%
28-day Compression strength tests (ASTM C 39): 5849 & 5857, avg = 5853 psi
Flexural test (AASHTO T 97) broken at 7 days: 885 psi
Flexural test (AASHTO T 97) broken at 28 days: 985 psi
Slump: 7.25"
Air Content: 1.3%
Unit Weight Concrete: 150.512 (lbs/cubic foot)
Water/Cement Ratio: 0.435
Concrete Temperature: 80^0 F

Table C4. Meridian Granite with Cement and Slag ASTM C 1293 Results

7 Days	28 Days	56 Days	3 Months	6 Months	9 Months	1 Year	1.5 Years	2 Years
-0.0098%	-0.0035%	-0.0007%	0.0020%	0.0069%	0.0131%	0.0166%	0.0295%	0.0403%

Mix: Meridian Granite with Cement and Fly Ash

Date of Mix: 7/12/2006
Time of Mix: 1:39 PM
Temperature at Time of Mixing: 74^0 F

Table C5. Meridian Granite with Cement and Fly Ash Mix Design

	Component	Specific Gravity	Absorption	Mass (kg)	Volume (ft^3)
Coarse Aggregate	Meridian Granite	2.634	0.74%	53.009	0.7110
Fine Aggregate	Cantley	2.693	0.40%	32.873	0.4313
Cement	Saint Lawrence Mississauga	3.15		14.570	0.1634
Fly Ash	Coal Creek	2.50		6.245	0.0883
Water		1		9.055	0.3199
Air (2% assumed)					0.0350
NaOH		2.13		0.067	0.0011
Total Volume					1.7500

Dry Rodded Unit Weight Coarse Aggregate: 95.4 lb/ft^3
Moisture of Fine Aggregate: 3.89%
Moisture of Coarse Aggregate: 2.65%
28-day Compression strength tests (ASTM C 39): 5419 & 5491, avg = 5455 psi
Flexural test (AASHTO T 97) broken at 7 days: 580 psi
Flexural test (AASHTO T 97) broken at 28 days: 910 psi
Slump: 8.75"
Air Content: 0.8%
Unit Weight Concrete: 150.704 (lbs/ft^3)
Water/Cement Ratio: 0.435
Concrete Temperature: 80^0 F

Table C6. Meridian Granite with Cement and Fly Ash ASTM C 1293 Results

7 Days	28 Days	56 Days	3 Months	6 Months	9 Months	1 Year	1.5 Years	2 Years
-0.0074%	-0.0064%	-0.0063%	-0.0053%	-0.0026%	0.0009%	0.0004%	0.0052%	0.0085%

Mix: Taconite LC-5 with Cement Only

Date of Mix: 6/28/2006
Time of Mix: 7:23 AM
Temperature at Time of Mixing: 75^0 F

Table C7. Taconite LC-5 with Cement Only Mix Design

	Component	Specific Gravity	Absorption	Mass (kg)	Volume (ft^3)
Coarse Aggregate	Taconite LC-5	3.304	0.54%	59.844	0.6399
Fine Aggregate	Cantley	2.693	0.40%	39.658	0.5203
Cement	Saint Lawrence Mississauga	3.15		20.815	0.2335
Water		1		9.055	0.3199
Air (2% assumed)					0.0350
NaOH		2.13		0.085	0.0014
Total Volume					1.7500

Dry Rodded Unit Weight Coarse Aggregate: 107.7 lb/ft^3
Moisture of Fine Aggregate: 3.76%
Moisture of Coarse Aggregate: 2.21%
28-day Compression strength tests (ASTM C 39): 6780 & 6987, avg = 6884 psi
Flexural test (AASHTO T 97) broken at 7 days: 955 psi
Flexural test (AASHTO T 97) broken at 28 days: 1000+ psi
Slump: 1.25"
Air Content: 0.8%
Unit Weight Concrete: 168.760 (lbs/ft^3)
Water/Cement Ratio: 0.435
Concrete Temperature: 82^0 F

Table C8. Taconite LC-5 with Cement Only ASTM C 1293 Results

7 Days	28 Days	56 Days	3 Months	6 Months	9 Months	1 Year	1.5 Years	2 Years
-0.0045%	0.0038%	0.0191%	0.0589%	0.1324%	0.1730%	0.1951%	0.2278%	0.2446%

Mix: Taconite LC-5 with Cement and Slag

Date of Mix: 7/5/2006
Time of Mix: 8:25 AM
Temperature at Time of Mixing: 72^0 F

Table C9. Taconite LC-5 with Cement and Slag Mix Design

	Component	Specific Gravity	Absorption	Mass (kg)	Volume (ft^3)
Coarse Aggregate	Taconite LC-5	3.304	0.54%	59.844	0.6399
Fine Aggregate	Cantley	2.693	0.40%	39.244	0.5149
Cement	Saint Lawrence Mississauga	3.15		13.530	0.1518
Slag	Holcim Grancem GR-100	2.96		7.285	0.0869
Water		1		9.055	0.3199
Air (2% assumed)					0.0350
NaOH		2.13		0.099	0.0016
Total Volume					1.7500

Dry Rodded Unit Weight Coarse Aggregate: 107.7 lb/ft^3
Moisture of Fine Aggregate: 3.46%
Moisture of Coarse Aggregate: 2.38%
28-day Compression strength tests (ASTM C 39): 6064 & 6080, avg = 6072 psi
Flexural test (AASHTO T 97) broken at 7 days: 925 psi
Flexural test (AASHTO T 97) broken at 28 days: 1000+ psi
Slump: 3.0"
Air Content: 1.4%
Unit Weight Concrete: 167.160 (lbs/ft^3)
Water/Cement Ratio: 0.435
Concrete Temperature: 81^0 F

Table C10. Taconite LC-5 with Cement and Slag ASTM C 1293 Results

7 Days	28 Days	56 Days	3 Months	6 Months	9 Months	1 Year	1.5 Years	2 Years
-0.0087%	-0.0032%	0.0014%	0.0095%	0.0431%	0.0726%	0.0900%	0.1126%	0.1306%

Mix: Taconite LC-5 with Cement and Fly Ash

Date of Mix: 7/5/2006
Time of Mix: 9:02 AM
Temperature at Time of Mixing: 72^0 F

Table C11. Taconite LC-5 with Cement and Fly Ash Mix Design

	Component	Specific Gravity	Absorption	Mass (kg)	Volume (ft^3)
Coarse Aggregate	Taconite LC-5	3.304	0.54%	59.844	0.6399
Fine Aggregate	Cantley	2.693	0.40%	38.292	0.5024
Cement	Saint Lawrence Mississauga	3.15		14.570	0.1634
Fly Ash	Coal Creek	2.50		6.245	0.0883
Water		1		9.055	0.3199
Air (2% assumed)					0.0350
NaOH		2.13		0.067	0.0011
Total Volume					1.7500

Dry Rodded Unit Weight Coarse Aggregate: 107.7 lb/ft^3
Moisture of Fine Aggregate: 3.46%
Moisture of Coarse Aggregate: 1.82%
28-day Compression strength tests (ASTM C 39): 5308 & 5268, avg = 5288 psi
Flexural test (AASHTO T 97) broken at 7 days: 645 psi
Flexural test (AASHTO T 97) broken at 28 days: 920 psi
Slump: 7.75"
Air Content: 1.7%
Unit Weight Concrete: 164.712 (lbs/ft^3)
Water/Cement Ratio: 0.435
Concrete Temperature: 79^0 F

Table C12. Taconite LC-5 with Cement and Fly Ash ASTM C 1293 Results

7 Days	28 Days	56 Days	3 Months	6 Months	9 Months	1 Year	1.5 Years	2 Years
-0.0074%	-0.0050%	-0.0048%	-0.0020%	0.0030%	0.0079%	0.0106%	0.0195%	0.0270%

Mix: Taconite LC-8 with Cement Only

Date of Mix: 5/24/2006
Time of Mix: 8:13 AM
Temperature at Time of Mixing: 72^0 F

Table C13. Taconite LC-8 with Cement Only Mix Design

	Component	Specific Gravity	Absorption	Mass (kg)	Volume (ft^3)
Coarse Aggregate	Taconite LC-8	3.089	1.23%	55.637	0.6363
Fine Aggregate	Cantley	2.693	0.40%	39.932	0.5239
Cement	Saint Lawrence Mississauga	3.15		20.815	0.2335
Water		1		9.055	0.3199
Air (2% assumed)					0.0350
NaOH		2.13		0.085	0.0014
Total Volume					1.7500

Dry Rodded Unit Weight Coarse Aggregate: 100.13 lb/ft^3
Moisture of Fine Aggregate: 5.80%
Moisture of Coarse Aggregate: 3.62%
28-day Compression strength tests (ASTM C 39): 6287 & 6645, avg = 6466 psi
Flexural test (AASHTO T 97) broken at 28 days: 960 psi
Slump: 1.75"
Air Content: 1.6%
Unit Weight Concrete: 163.360 (lbs/ft^3)
Water/Cement Ratio: 0.435
Concrete Temperature: 79^0 F

Table C14. Taconite LC-8 with Cement Only ASTM C 1293 Results

7 Days	28 Days	56 Days	3 Months	6 Months	9 Months	1 Year	1.5 Years	2 Years
0.0001%	0.0088%	0.0105%	0.0146%	0.0190%	0.0213%	0.0218%	0.0258%	0.0279%

Mix: Taconite LC-8 with Cement and Slag

Date of Mix: 5/31/2006
Time of Mix: 9:08 AM
Temperature at Time of Mixing: 74^0 F

Table C15. Taconite LC-8 with Cement and Slag Mix Design

	Component	Specific Gravity	Absorption	Mass (kg)	Volume (ft^3)
Coarse Aggregate	Taconite LC-8	3.089	1.23%	55.637	0.6363
Fine Aggregate	Cantley	2.693	0.40%	39.518	0.5185
Cement	Saint Lawrence Mississauga	3.15		13.530	0.1518
Slag	Holcim Grancem GR-100	2.96		7.285	0.0869
Water		1		9.055	0.3199
Air (2% assumed)					0.0350
NaOH		2.13		0.099	0.0016
Total Volume					1.7500

Dry Rodded Unit Weight Coarse Aggregate: 100.13 lb/ft^3
Moisture of Fine Aggregate: 7.03%
Moisture of Coarse Aggregate: 3.13%
28-day Compression strength tests (ASTM C 39): 6875 & 6685, avg = 6780 psi
Flexural test (AASHTO T 97) broken at 28 days: 1000+ psi
Slump: 1.75"
Air Content: 0.3%
Unit Weight Concrete: 163.232 (lbs/ft^3)
Water/Cement Ratio: 0.435
Concrete Temperature: 82^0 F

Table C16. Taconite with Cement and Slag ASTM C 1293 Results

7 Days	28 Days	56 Days	3 Months	6 Months	9 Months	1 Year	1.5 Years	2 Years
-0.0043%	0.0040%	0.0051%	0.0090%	0.0115%	0.0141%	0.0144%	0.0184%	0.0209%

Mix: Taconite LC-8 with Cement and Fly Ash

Date of Mix: 5/31/2006
Time of Mix: 8:23 AM
Temperature at Time of Mixing: 74^0 F

Table C17. Taconite LC-8 with Cement and Fly Ash Mix Design

	Component	Specific Gravity	Absorption	Mass (kg)	Volume (ft^3)
Coarse Aggregate	Taconite LC-8	3.089	1.23%	55.637	0.6363
Fine Aggregate	Cantley	2.693	0.40%	38.564	0.5059
Cement	Saint Lawrence Mississauga	3.15		14.570	0.1634
Fly Ash	Coal Creek	2.50		6.245	0.0883
Water		1		9.055	0.3199
Air 2% (assumed)					0.0350
NaOH		2.13		0.067	0.0011
Total Volume					1.7500

Dry Rodded Unit Weight Coarse Aggregate: 100.13 lb/ft^3
Moisture of Fine Aggregate: 7.03%
Moisture of Coarse Aggregate: 3.38%
28-day Compression strength tests (ASTM C 39): 5547 & 5658, avg = 5602 psi
Flexural test (AASHTO T 97) broken at 28 days: 825 psi
Slump: 6.5"
Air Content: 0.8%
Unit Weight Concrete: 161.416 (lbs/ft^3)
Water/Cement Ratio: 0.435
Concrete Temperature: 78^0 F

Table C18. Taconite LC-8 with Cement and Fly Ash ASTM C 1293 Results

7 Days	28 Days	56 Days	3 Months	6 Months	9 Months	1 Year	1.5 Years	2 Years
-0.0033%	0.0016%	0.0036%	0.0041%	0.0076%	0.0096%	0.0095%	0.0139%	0.0168%

Mix: Taconite LUC with Cement Only

Date of Mix: 6/7/2006
Time of Mix: 8:27 AM
Temperature at Time of Mixing: 74^0 F

Table C19. Taconite LUC with Cement Only Mix Design

	Component	Specific Gravity	Absorption	Mass (kg)	Volume (ft^3)
Coarse Aggregate	Taconite LUC	3.117	1.07%	56.621	0.6418
Fine Aggregate	Cantley	2.693	0.40%	39.516	0.5184
Cement	Saint Lawrence Mississauga	3.15		20.815	0.2335
Water		1		9.055	0.3199
Air 2% (assumed)					0.0350
NaOH		2.13		0.085	0.0014
Total Volume					1.7500

Dry Rodded Unit Weight Coarse Aggregate: 101.9 lb/ft^3
Moisture of Fine Aggregate: 3.69%
Moisture of Coarse Aggregate: 3.20%
28-day Compression strength tests (ASTM C 39): 6310 & 6271, avg = 6290 psi
Flexural test (AASHTO T 97) broken at 7 days: 885 psi
Flexural test (AASHTO T 97) broken at 28 days: 930 psi
Slump: 3.75"
Air Content: 2.1%
Unit Weight Concrete: 161.488 (lbs/ft^3)
Water/Cement Ratio: 0.435
Concrete Temperature: 78^0 F

Table C20. Taconite LUC with Cement Only ASTM C 1293 Results

7 Days	28 Days	56 Days	3 Months	6 Months	9 Months	1 Year	1.5 Years	2 Years
-0.0020%	0.0064%	0.0115%	0.0148%	0.0214%	0.0273%	0.0286%	0.0336%	0.0364%

Mix: Taconite LUC with Cement and Slag

Date of Mix: 6/7/2006
Time of Mix: 9:02 AM
Temperature at Time of Mixing: 70^0 F

Table C21. Taconite LUC with Cement and Slag Mix Design

	Component	Specific Gravity	Absorption	Mass (kg)	Volume (ft^3)
Coarse Aggregate	Taconite LUC	3.117	1.07%	56.621	0.6418
Fine Aggregate	Cantley	2.693	0.40%	39.103	0.5130
Cement	Saint Lawrence Mississauga	3.15		13.530	0.1518
Slag	Holcim Grancem GR-100	2.96		7.285	0.0869
Water		1		9.055	0.3199
Air 2% Assumed					0.0350
NaOH		2.13		0.099	0.0016
Total Volume					1.7500

Dry Rodded Unit Weight Coarse Aggregate: 101.9 lb/ft^3
Moisture of Fine Aggregate: 3.69%
Moisture of Coarse Aggregate: 2.58%
28-day Compression strength tests (ASTM C 39): 5968 & 5849, avg = 5908 psi
Flexural test (AASHTO T 97) broken at 7 days: 850 psi
Flexural test (AASHTO T 97) broken at 28 days: 1000+ psi
Slump: 3.75"
Air Content: 1.9%
Unit Weight Concrete: 161.096 (lbs/ft^3)
Water/Cement Ratio: 0.435
Concrete Temperature: 78^0 F

Table C22. Taconite LUC with Cement and Slag ASTM C 1293 Results

7 Days	28 Days	56 Days	3 Months	6 Months	9 Months	1 Year	1.5 Years	2 Years
-0.0050%	0.0025%	0.0074%	0.0081%	0.0115%	0.0155%	0.0161%	0.0200%	0.0228%

Mix: Taconite LUC with Cement and Fly Ash

Date of Mix: 6/14/2006
Time of Mix: 8:25 AM
Temperature at Time of Mixing: 72^0 F

Table C23. Taconite LUC with Cement and Fly Ash Mix Design

	Component	Specific Gravity	Absorption	Mass (kg)	Volume (ft^3)
Coarse Aggregate	Taconite LUC	3.117	1.07%	56.621	0.6418
Fine Aggregate	Cantley	2.693	0.40%	38.150	0.5005
Cement	Saint Lawrence Mississauga	3.15		14.570	0.1634
Fly Ash	Coal Creek	2.50		6.245	0.0883
Water		1		9.055	0.3199
Air 2% (assumed)					0.0350
NaOH		2.13		0.067	0.0011
Total Volume					1.7500

Dry Rodded Unit Weight Coarse Aggregate: 101.9 lb/ft^3
Moisture of Fine Aggregate: 4.55%
Moisture of Coarse Aggregate: 2.81%
28-day Compression strength tests (ASTM C 39): 5260 & 5491, avg = 5376 psi
Flexural test (AASHTO T 97) broken at 7 days: 625 psi
Flexural test (AASHTO T 97) broken at 28 days: 845 psi
Slump: 6.25"
Air Content: 2.2%
Unit Weight Concrete: 159.704 (lbs/ft^3)
Water/Cement Ratio: 0.435
Concrete Temperature: 78^0 F

Table C24. Taconite LUC with Cement and Fly Ash ASTM C 1293 Results

7 Days	28 Days	56 Days	3 Months	6 Months	9 Months	1 Year	1.5 Years	2 Years
-0.0031%	-0.0009%	0.0011%	0.0017%	0.0045%	0.0076%	0.0076	0.0119%	0.0140%

Mix: Taconite LS-2 with Cement Only

Date of Mix: 6/21/2006
Time of Mix: 8:37 AM
Temperature at Time of Mixing: 74^0 F

Table C25. Taconite LS-2 with Cement Only Mix Design

	Component	Specific Gravity	Absorption	Mass (kg)	Volume (ft^3)
Coarse Aggregate	Taconite LS-2	2.868	1.80%	51.120	0.6297
Fine Aggregate	Cantley	2.693	0.40%	40.434	0.5305
Cement	Saint Lawrence Mississauga	3.15		20.815	0.2335
Water		1		9.055	0.3199
Air 2% (assumed)					0.0350
NaOH		2.13		0.085	0.0014
Total Volume					1.7500

Dry Rodded Unit Weight Coarse Aggregate: 92.0 lb/ft^3
Moisture of Fine Aggregate: 2.98%
Moisture of Coarse Aggregate: 4.13%
28-day Compression strength tests (ASTM C 39): 6255 & 6326, avg = 6290 psi
Flexural test (AASHTO T 97) broken at 7 days: 800 psi
Flexural test (AASHTO T 97) broken at 28 days: 960 psi
Slump: 2.5"
Air Content: 1.0%
Unit Weight Concrete: 157.424 (lbs/ft^3)
Water/Cement Ratio: 0.435
Concrete Temperature: 81^0 F

Table C26. Taconite LS-2 with Cement Only ASTM C 1293 Results

7 Days	28 Days	56 Days	3 Months	6 Months	9 Months	1 Year	1.5 Years	2 Years
-0.0048%	0.0054%	0.0114%	0.0150%	0.0189%	0.0229%	0.0234%	0.0269%	0.0291%

Mix: Taconite LS-2 with Cement and Slag

Date of Mix: 6/212006
Time of Mix: 9:17 AM
Temperature at Time of Mixing: 74^0 F

Table C27. Taconite LS-2 with Cement Only Mix Design

	Component	Specific Gravity	Absorption	Mass (kg)	Volume (ft^3)
Coarse Aggregate	Taconite LS-2	2.868	1.80%	51.120	0.6297
Fine Aggregate	Cantley	2.693	0.40%	40.024	0.5251
Cement	Saint Lawrence Mississauga	3.15		13.530	0.1518
Slag	Holcim Grancem GR-100	2.96		7.285	0.0869
Water		1		9.055	0.3199
Air 2% (assumed)					0.0350
NaOH		2.13		0.099	0.0016
Total Volume					1.7500

Dry Rodded Unit Weight Coarse Aggregate: 92.0 lb/ft^3
Moisture of Fine Aggregate: 2.98%
Moisture of Coarse Aggregate: 3.67%
28-day Compression strength tests (ASTM C 39): 5825 & 5849, avg = 5837 psi
Flexural test (AASHTO T 97) broken at 7 days: 800 psi
Flexural test (AASHTO T 97) broken at 28 days: 905 psi
Slump: 3.0"
Air Content: 1.1%
Unit Weight Concrete: 156.592 (lbs/ft^3)
Water/Cement Ratio: 0.435
Concrete Temperature: 81^0 F

Table C28. Taconite LS-2 with Cement and Slag ASTM C 1293 Results

7 Days	28 Days	56 Days	3 Months	6 Months	9 Months	1 Year	1.5 Years	2 Years
-0.0066%	0.0011%	0.0071%	0.0105%	0.0149%	0.0188%	0.0193%	0.0243%	0.0269%

Mix: Taconite LS-2 with Cement and Fly Ash

Date of Mix: 6/28/2006
Time of Mix: 8:01 AM
Temperature at Time of Mixing: 74^0 F

Table C29. Taconite LS-2 with Cement and Fly Ash Mix Design

	Component	Specific Gravity	Absorption	Mass (kg)	Volume (ft^3)
Coarse Aggregate	Taconite LS-2	2.868	1.80%	51.120	0.6297
Fine Aggregate	Cantley	2.693	0.40%	39.068	0.5125
Cement	Saint Lawrence Mississauga	3.15		14.570	0.1634
Fly Ash	Coal Creek	2.50		6.245	0.0883
Water		1		9.055	0.3199
Air 2% (assumed)					0.0350
NaOH		2.13		0.067	0.0011
Total Volume					1.7500

Dry Rodded Unit Weight Coarse Aggregate: 92.0 lb/ft^3
Moisture of Fine Aggregate: 3.76%
Moisture of Coarse Aggregate: 3.82%
28-day Compression strength tests (ASTM C 39): 5435 & 5491, avg = 5463 psi
Flexural test (AASHTO T 97) broken at 7 days: 630 psi
Flexural test (AASHTO T 97) broken at 28 days: 860 psi
Slump: 5.5"
Air Content: 2.4%
Unit Weight Concrete: 156.736 (lbs/ft^3)
Water/Cement Ratio: 0.435
Concrete Temperature: 80^0 F

Table C30. Taconite LS-2 with Cement and Fly Ash ASTM C 1293 Results

7 Days	28 Days	56 Days	3 Months	6 Months	9 Months	1 Year	1.5 Years	2 Years
-0.0058%	-0.0034%	-0.0009%	0.0025%	0.0051%	0.0081%	0.0079%	0.0134%	0.0166%

Mix: Taconite LC-5 Redo with Cement Only, Vibrated Beams

Date of Mix: 1/4/2007
Time of Mix: 10:15 AM
Temperature at Time of Mixing: 68^0 F

Table C31. Taconite LC-5 with Cement Only, Vibrated Beams Mix Design

	Component	Specific Gravity	Absorption	Mass (kg)	Volume (ft^3)
Coarse Aggregate	Taconite LC-5	3.304	0.54%	34.196	0.3657
Fine Aggregate	Cantley	2.693	0.40%	22.662	0.2973
Cement	Saint Lawrence Mississauga	3.15		11.894	0.1334
Water		1		5.174	0.1828
Air 2% (assumed)					0.0200
NaOH		2.13		0.049	0.0008
Total Volume					1.7500

Dry Rodded Unit Weight Coarse Aggregate: 107.7 lb/ft^3
Moisture of Fine Aggregate: 3.30%
Moisture of Coarse Aggregate: 1.96%
28-day Compression strength tests (ASTM C 39): 6000 & 6008, avg = 6004 psi
Slump: 4"
Air Content: 3.2%
Unit Weight Concrete: 163.384 (lbs/ft^3)
Water/Cement Ratio: 0.435
Concrete Temperature: 70^0 F

Table C32. Taconite LC-5 with Cement Only, Vibrated Beams ASTM C 1293 Results

7 Days	28 Days	56 Days	3 Months	6 Months	9 Months	1 Year	1.5 Years	2 Years
-0.0059%	0.0030%	0.0155%	0.0399%	0.1126%	0.1607%	0.1916%	0.2270%	Reading 1/2009

Mix: Taconite LC-5 Redo with Cement Only, Rodded Beams

Date of Mix: 1/4/2007
Time of Mix: 10:15 AM
Temperature at Time of Mixing: 68^0 F

Table C33. Taconite LC-5 Redo with Cement Only, Rodded Beams Mix Design

	Component	Specific Gravity	Absorption	Mass (kg)	Volume (ft^3)
Coarse Aggregate	Taconite LC-5	3.304	0.54%	34.196	0.3657
Fine Aggregate	Cantley	2.693	0.40%	22.662	0.2973
Cement	Saint Lawrence Mississauga	3.15		11.894	0.1334
Water		1		5.174	0.1828
Air 2% (assumed)					0.0200
NaOH		2.13		0.049	0.0008
Total Volume					1.7500

Dry Rodded Unit Weight Coarse Aggregate: 107.7 lb/ft^3
Moisture of Fine Aggregate: 3.30%
Moisture of Coarse Aggregate: 1.96%
28-day Compression strength tests (ASTM C 39): 6000 & 6008, avg = 6004 psi
Slump: 4"
Air Content: 3.2%
Unit Weight Concrete: 163.384 (lbs/ft^3)
Water/Cement Ratio: 0.435
Concrete Temperature: 70^0 F

Table C34. Taconite LC-5 Redo with Cement Only, Rodded ASTM C 1293 Results

7 Days	28 Days	56 Days	3 Months	6 Months	9 Months	1 Year	1.5 Years	2 Years
-0.0055%	0.0038%	0.0180%	0.0551%	0.1810%	0.2514%	0.2933%	0.3413%	Reading 1/2009

APPENDIX D - ASTM C 1293 ONE-YEAR RESULTS

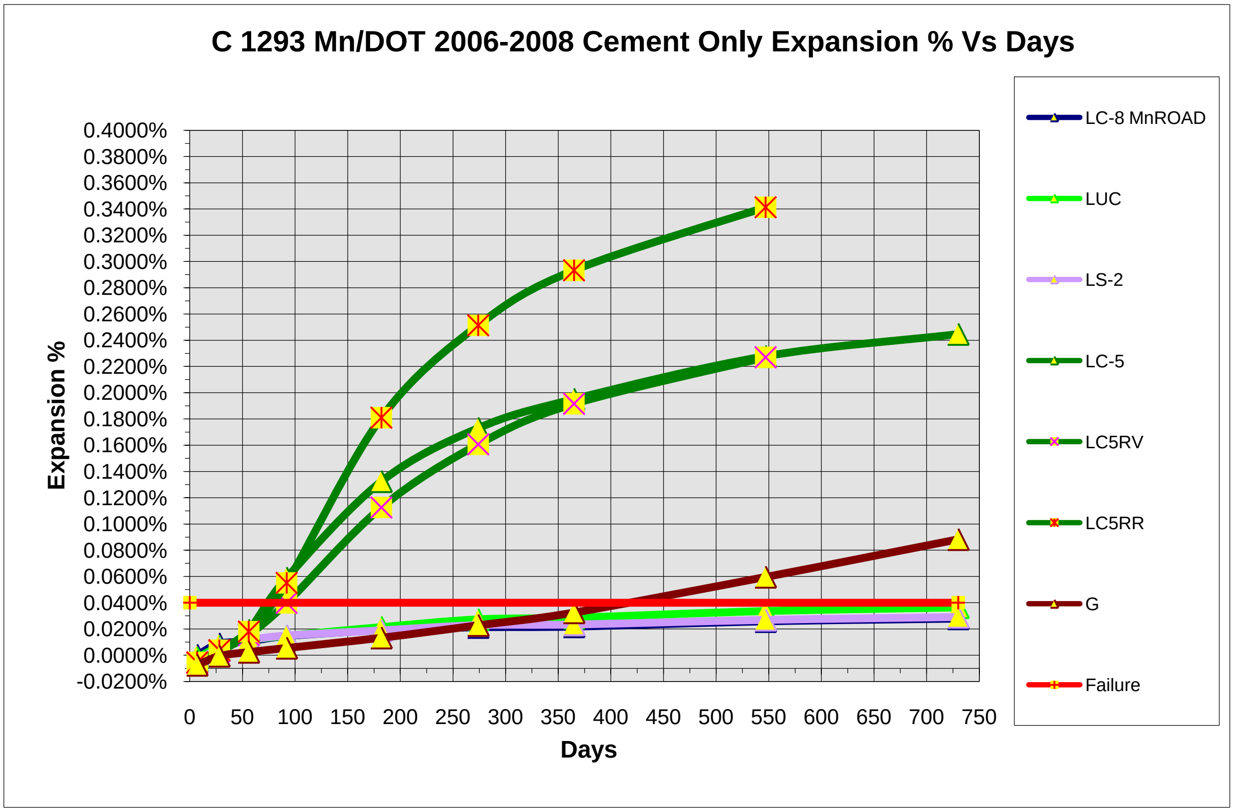

Figure D1. ASTM C 1293 Cement Only Test Results

Note: LC5RV is a redo mix of LC5 and was vibrated; LC5RR is a redo mix of LC5 and was rodded. G is for granite. Failure is based on a one-year reading of greater than 0.04%. LC5 mixes failed, all others passed.

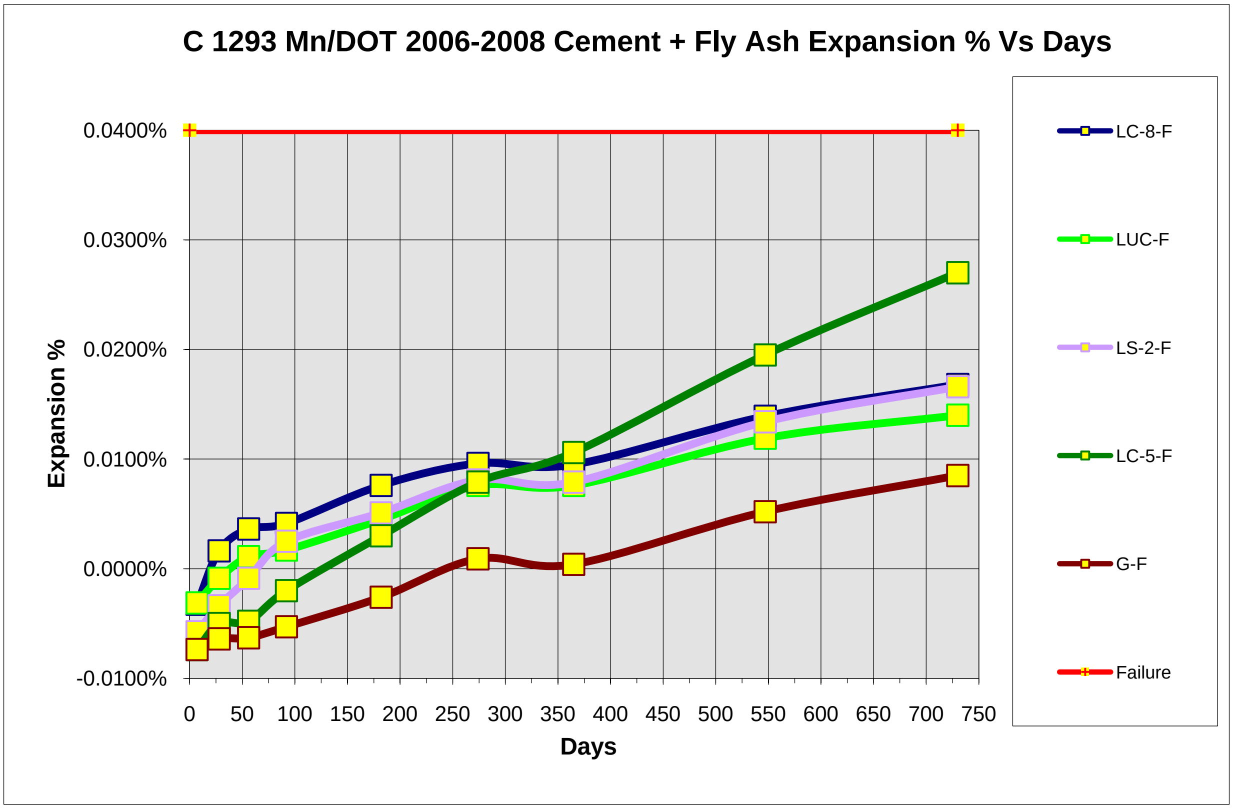

Figure D2. ASTM C 1293 Cement plus Fly Ash Test Results

Note: Failure is based on a two-year reading of greater than 0.04%. All mixes passed.
F indicates fly ash. G indicates granite.

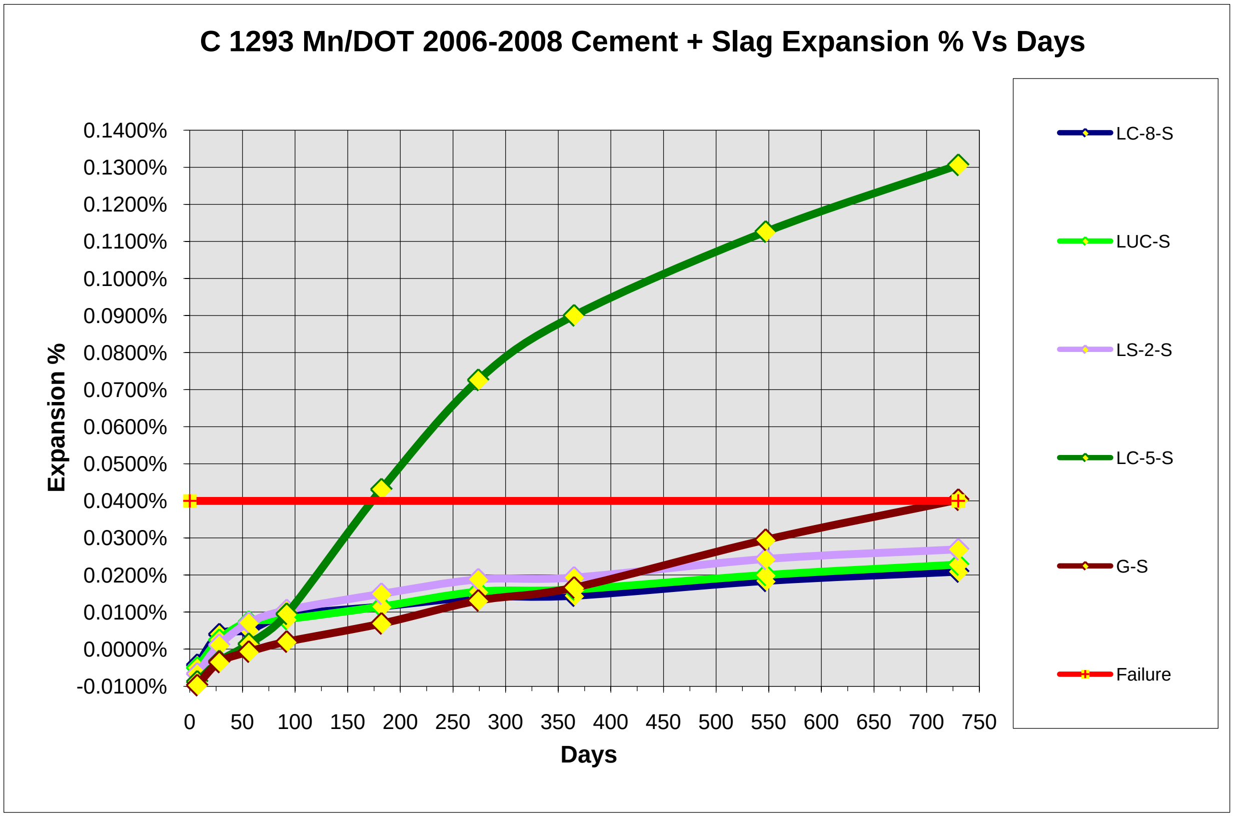

Figure D3. ASTM C 1293 Cement plus Slag Test Results

Note: Failure is based on a two-year reading of greater than 0.04%. LC5-S failed, and G-S was borderline, all other mixes passed. S indicates slag. G indicates granite.

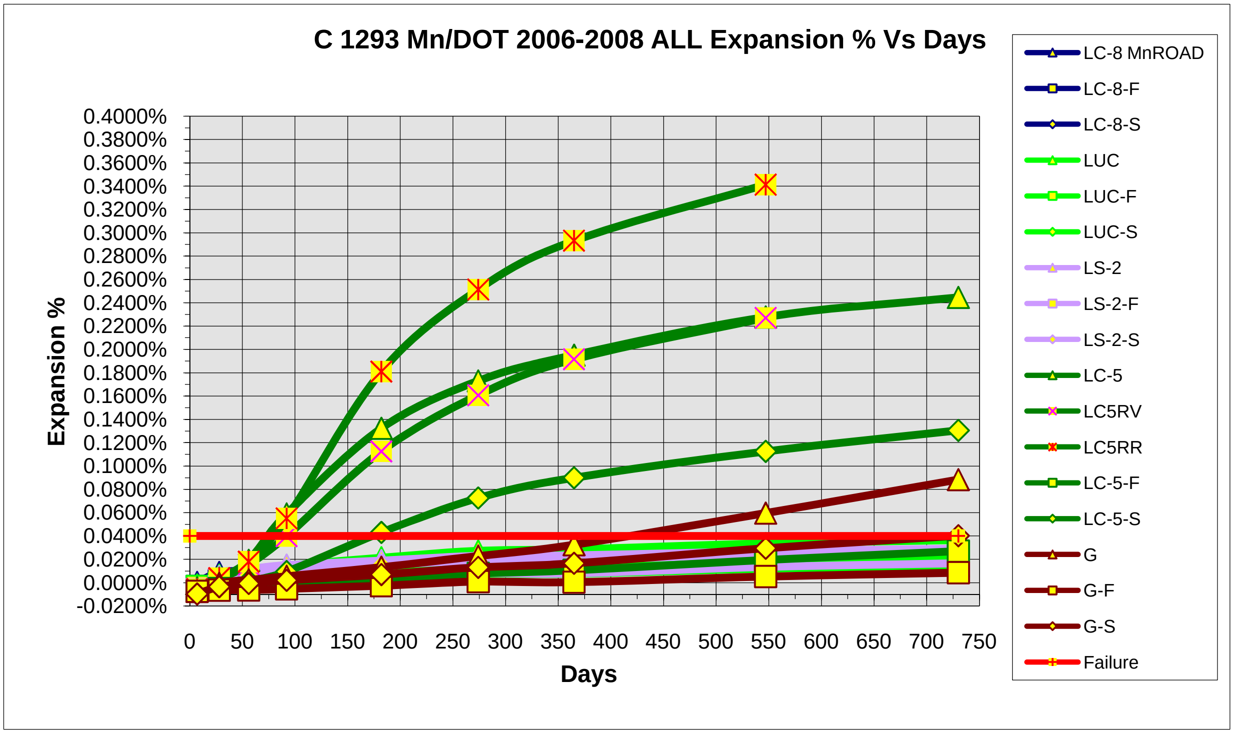

Figure D4. ASTM C 1293 All Expansion Test Results

Note: Failure is based on a one-year reading of greater than 0.04% for cement only mixes. Failure is based on a two-year reading of greater than 0.04% for slag and fly ash mixes. LC5RV is a redo mix of LC5 and was vibrated; LC5RR is a redo mix of LC5 and was rodded. F indicates fly ash, S indicates slag. G indicates granite.

APPENDIX E - ASTM C 1260 MORTAR BAR TESTS

Table E1. ASTM C 1260 Test Results for CANMET Sand

Test	Result
ASTM C 1260 Mortar Bar CANMET Holcim Cement 14 day, % Spec 0.165 max	0.0507%
ASTM C 1260 Mortar Bar CANMET Holcim Cement + Fly ash 14 day, % Spec 0.165 Max	0.0393%
ASTM C 1260 Mortar Bar CANMET Holcim Cement + Slag 14 day, % Spec 0.165 Max	0.0463%

Table E2. ASTM C 1260 Test Results for LC-5 Sand

Test	Result
ASTM C 1260 Mortar Bar Holcim Cement 14 day, % Spec 0.165 Max	0.3957%
ASTM C 1260 Mortar Bar Lafarge Cement 14 day, % Spec 0.165 Max	0.3730%

Table E3. ASTM C 1260 Test Results for LS-2 Sand

Test	Result
ASTM C 1260 Mortar Bar Holcim Cement 14 day, % Spec 0.165 Max	0.1087%
ASTM C 1260 Mortar Bar Lafarge Cement 14 day, % Spec 0.165 Max	0.1070%

Table E4. ASTM C 1260 Test Results for LC-8 Sand

Test	Result
ASTM C 1260 Mortar Bar Holcim Cement 14 day, % Spec 0.165 Max	0.0363%
ASTM C 1260 Mortar Bar Lafarge Cement 14 day, % Spec 0.165 Max	0.0440%

Table E5. ASTM C 1260 Test Results for LUC Sand

Test	Result
ASTM C 1260 Mortar Bar Holcim Cement 14 day, % Spec 0.165 Max	0.1891%
ASTM C 1260 Mortar Bar Lafarge Cement 14 day, % Spec 0.165 Max	0.1693%

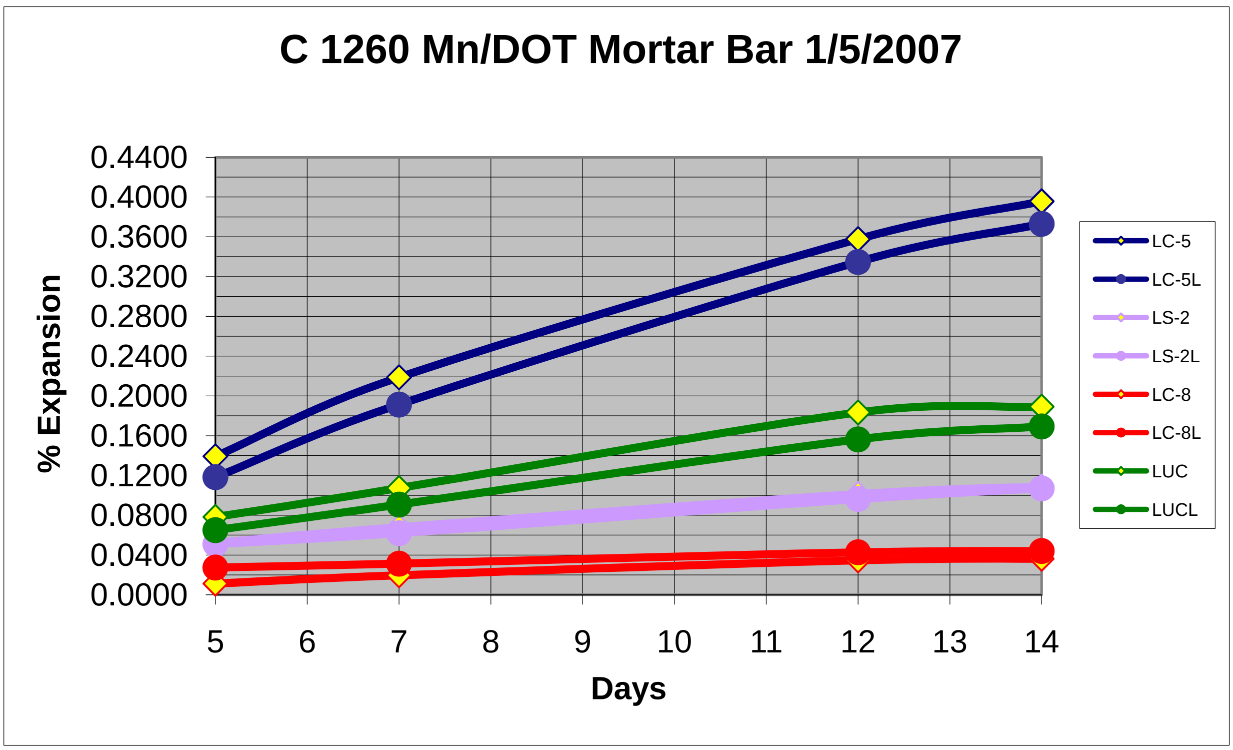

Figure E1. ASTM C 1260 Mortar Bar Expansions

ASTM C 1260 Mortar Bar Data showing expansion of four taconite rock strata. The "H" signifies Holcim cement, and the "L" signifies Lafarge cement.

Manufactured sand (sand produced by crushing coarse aggregate) is not allowed in concrete by Mn/DOT Specification, however, the ASTM C 1260 test is a good indicator of potential expansion of coarse aggregate used in concrete.

The Mn/DOT ASTM C 1260 failure criteria for a natural sand based on the expansion at fourteen days is the following:

"The higher expansion result of two cement and sand combinations shall determine what mitigation may be necessary. If the proposed fine aggregate results are:

(1) < or = to 0.150%	The fine aggregate is acceptable with or without a mitigator in the concrete mix.
(2) 0.151 - 0.250%	The fine aggregate shall be mitigated with 35% ground granulated blast furnace slag or a minimum of 20% fly ash.
(3) 0.251 - 0.300%	The fine aggregate shall be mitigated with 35% ground granulated blast furnace slag or 30% fly ash meeting Mn/DOT Spec 3115 modified with a minimum SiO_2 + Fe_2O_3 + Al_2O_3 of 66.0% on a dry weight basis and a minimum SiO_2 content of 38.0%.
(4) > 0.300%	The fine aggregate is rejected.

APPENDIX F – RESULTS OF MINERALOGICAL ANALYSIS OF TACONITE AGGREGATES

Table F1. LC-5 Bed (111-05) Ispat Inland/Mittal Steel (Laurentian Pit) Lithological Summary for Canadian Prism Test Samples 3/4"(-) to 1/2"(+) Jan-07

Siliceous/'Cherty'	**Mass (g)**	**Total (%)**
Type I/II	1524.5	28.2%
FeO/Hematite Rich	29.8	0.6%
FeS2 Rich	15.8	0.3%
Total	**1570.1**	**29.1%**

	Mass (g)	**Total (%)**
CO3-Rich/'Slatey'	0	0.0%
Total	**0**	**0.0%**

Magnetite Rich	**Mass (g)**	**Total (%)**
Siliceous/'Cherty'	3783.3	69.9%
Siliceous/Hema/FeO Rich	7.0	0.1%
CO3-Rich/'Slatey'?	50.5	0.9%
Total	**3840.8**	**70.9%**

	Mass (g)	**Total (%)**
Grand Total	**5410.9**	**100%**

	Mass (g)	**Total (%)**
% Siliceous/'Cherty'	**5360.4**	**99.1%**
%CO3- Rich/'Slatey'	**50.5**	**0.9%?**

Notes:

1. Virtually all of aggregates are Siliceous/'Cherty' as noted
2. Both Siliceous and Magnetite Rich varieties appear to be of the Type I Siliceous variety as referenced in mineralogical analysis of LC-8 bed (Embacher report)
   a) The aggregate texture is sometimes obscured by disseminated magnetite which also commonly occurs in bands (hence, the '?' next to CO3-Rich); consequently, some CO3-Rich aggregates may have been misclassified due to the textural similarites between CO3-Rich and Siliceous Magnetite-Rich aggregates
   b) Chert content, as opposed to recrystallized quartz, may be in fair to high amounts given the presence of a white weathering product (typically found on weathered cherts) found on several aggregate surfaces
   c) Greenalite, as opposed to minnesotaite, appears to be quite common in voids and matrix (greenalite was commonly found associated w/ magnetite in thin sections prepared for the Embacher report)

Table F2. LC-8 Bed (111-05) United Taconite Lithological Summary for Canadian Prism Test Samples 3/4"(-) to 1/2"(+) Jan-07

Siliceous/'Cherty'	**Mass (g)**	**Total (%)**
Type I/II	2208.8	44.3%
Chert	68.9	1.4%
Wx Type I/II/Chert	98.6	2.0%
MNite Rich Chert	42.9	0.9%
FeO/Hema. Rich Chert	26.4	0.5%
Total	**2445.6**	**49.1%**

CO3-Rich/'Slatey'	**Mass (g)**	**Total (%)**
Siderite-Rich	685.2	13.8%
Cherty Sid.-Rich	69.9	1.3%
MetaSid-Rich	27.2	0.5%
CO3-Rich Aggregate?	63.4	1.3%
Total	**845.7**	**17.0%**

Magnetite Rich	**Mass (g)**	**Total (%)**
Siliceous/'Cherty'	779.6	15.6%
CO3-Rich/'Slatey'	526.5	10.6%
Total	**1306.1**	**26.2%**

Miscellaneous	**Mass (g)**	**Total (%)**
Interblended 'Cherty' & 'Slatey'	384.1	7.7%
Total	384.1	**7.7%**

	Mass (g)	**Total (%)**
Grand Total	**4981.5**	**100%**

	Mass (g)	**Total (%)**
% Siliceous/'Cherty'	**3417.3**	**68.6%**
%CO3- Rich/'Slatey'	**1494.4**	**31.4%**

Notes:

1. Siliceous fraction is mostly composed of Type I and II (clarified in report to Embacher)
   a) Some Cherty Sid.-Rich aggregates may have been considered siliceous given characteristics deceptively similar to Cherty Type I aggregates
   b) Several weathered forms of Type I/II were considered unweathered in order to expedite the summary (this does not affect the siliceous %'s); additionally, it is likely that not all cherts were delineated from Type I/II's
2. 'CO3-Rich aggregate?' may be a weathered form of Cherty Sid.-Rich
3. Since 'Interbedded 'Cherty' and 'Slatey' aggregates are comprised of both material types, the mass of this material was divided in two and distributed evenly between the total percent for Siliceous material and CO3-Rich material

Table F3. LS-2 Bed (100-05) Ispat Inland/Mittal Steel (Laurentian Pit) Lithological Summary for Canadian Prism Test Samples 3/4"(-) to 1/2"(+) Jan-07

Siliceous/'Cherty'	**Mass (g)**	**Total (%)**
Type I/II	2815.9	55.0%
Chert	181.2	3.5%
Wx Type I/II/Chert	6.7	0.1%
FeO/Hematite Rich	2.2	0.1%
Total	**3003.0**	**58.6%**

CO3-Rich/'Slatey'	**Mass (g)**	**Total (%)**
Siderite-Rich	1856.1	36.3%
Wx Sid.-Rich	20.9	0.4%
Total	**1877.0**	**36.7%**

Magnetite Rich	**Mass (g)**	**Total (%)**
Siliceous	44.1	0.9%
CO3-Rich	62.3	1.2%
Total	**106.4**	**2.1%**

Miscellaneous	**Mass (g)**	**Total (%)**
CO3-Rich/'Slatey Mottled w/ Quartz	130.0	2.5%
Total	**130.0**	**2.5%**

	Mass (g)	**Total (%)**
Grand Total	**5116.4**	**100%**

	Mass (g)	**Total (%)**
% Siliceous/'Cherty'	**3112.1**	**60.8%**
%CO3- Rich/'Slatey'?	**2004.3**	**39.2%**

Notes:

1. Siliceous fraction is mostly composed of Type I and II (clarified in report to Embacher)
   a) Some Cherty Sid.-Rich aggregates may have been considered siliceous given characteristics deceptively similar to Type I aggregates; Chert is recognizable by its lack of surface texture; It is possible that not all cherts were distinguished from Type I/II's (this does not affect the Sil. %'s)
   b) The mostly greenish hue of the Siliceous fraction may be indicative of a high minnesotaite concentration
2. The CO3-Rich/'Slatey' fraction contains several aggregates which would likely fail MnDOT's 'flat and elongated' specification
3. Since 'CO3-Rich/'Slatey' Mottled w/ Quartz' aggregates are comprised of carbonate and silica, the mass of this material was divided in two and distributed evenly between the total percents for Siliceous material and CO3-Rich

Table F4. LUC Bed (114-05) United Taconite Lithological Summary for Canadian Prism Test Samples 3/4"(-) to 1/2"(+) Jan-07

Siliceous/'Cherty'	**Mass (g)**	**Total (%)**
Crystalline/Hematitic	1526.6	29.7%
Weathered/Unsound variety of above	106.1	2.0%
Chert-Rich variety	361.6	7.0%
Weathered/Unsound Chert-Rich variety	14.8	0.3%
Total	**2009.1**	**39.0%**

	Mass (g)	**Total (%)**
CO3-Rich/'Slatey'	1148.8	22.3%
Total	**1148.8**	**22.3%**

Magnetite Rich	**Mass (g)**	**Total (%)**
Siliceous/'Cherty'	232.7	4.5%
CO3-Rich/'Slatey'	1266.1	24.6%
Interbedded 'Cherty' & 'Slatey'	112.9	2.2%
Weathered CO3 Rich/'Slatey' or Ashflow	141.0	2.7%
Total	**1752.7**	**34.0%**

Misc.	**Mass (g)**	**Total (%)**
Interbedded 'Cherty' & 'Slatey'	188.2	3.7%
Weathered CO3 Rich/'Slatey' or Ashflow	49.4	1.0%
TOTAL	**5148.2**	**100%**

	Mass (g)	**Total (%)**
Grand Total	5148.2	100%

	Mass (g)	**Total (%)**
% Siliceous/'Cherty'	2392.4	46.5%
%CO3- Rich/'Slatey'?	2755.8	53.5%

Notes:

1. Siliceous/'Cherty' fraction displays varying concentrations of hematite (creates a vivid color distinction when compared to the green to black LS-2, LC-5 and LC-8 samples
2. Siliceous/'Cherty' fraction displays varying degrees of chemical weathering in cherty ooids found in the Crystalline/Hematitic variety
3. Many of the 'Cherty variety' of the Siliceous/'Cherty' fraction may have appreciable carbonate contents within the cherty matrix based on similar color observations documented in the report to Embacher and verified petrographically
4. Since 'Interbedded Cherty & Slatey' aggregates are comprised of both material types, the mass of this material was divided in two and distributed evenly between the total percent for Siliceous material and CO3-Rich material5.) Since petrographic work was not performed, material identified as 'Ashflow' will be considered Weathered 'Slatey' material for statistical purposes.

Minnesota Department of Transportation

Memo

Office of Materials
Geotechnical Engineering Section
Mail Stop 645
1400 Gervais Ave
Maplewood MN 55109

Office: (651) 779-5607
Fax: (651) 779-5510

Date May 12, 2005

To: Rebecca Embacher, PE
Senior Engineer

From: Jason Richter, PG
Geologist

Subject: Results of Mineralogical Analysis of Taconite Aggregate

At your request, mineralogical analyses were performed on the Mesabi Select aggregate taken from a stockpile (-2 inch size) at Mn/Road comprised of crushed material obtained from the top 25 feet of the 'Lower Cherty' member, or LC-8 bed (LC-6 bed in NRRI study), of the United Taconite mine near Eveleth. Taconite from the LC-8 ledge was utilized in asphalt (-3/4"/cell 32) and concrete pavement (-2"/cell 54) constructed at Mn/Road.

Fig. 1: Photo of Lower Cherty Member ledge face (LC-8 bed) showing alternating beds of thin-bedded carbonate-rich rock and thicker-bedded silica-rich rock.

Analyses suggest that about 90 to 95% of the aggregate particles, by volume, in the sample can be categorized as either silica-rich, carbonate-rich or a combination of the two (Fig. 1). The *silica-rich* component comprises about 60% (+/-5%) of all particles and consists of two varieties of a siliceous rock type as well as a lesser chert fraction. The *carbonate-rich* component comprises about 30% (+/-5%) of all particles and consists primarily of a siderite-rich rock type but also includes a chert-rich variant and, to a lesser extent, a highly-deformed variant. The remaining 5 to 10% of the sample can be categorized as *magnetite-rich*, but is essentially an iron-rich variant of rocks comprising the *silica-rich* and *carbonate-rich* classes.

Notes: The percentages above were not obtained from inspection and sampling of a ledge face, but were acquired via megascopic examination (lithological summary) of aggregate particles retrieved from a Mn/Road stockpile composed of –2 inch aggregate. Representative aggregate particles from each rock type identified during the lithological summary were selected for thin section production, which allowed for lithologic verification of hand samples (thin sections from a previous taconite analysis performed for Nancy Whiting (2/3/04) were also used in this analysis). The sample size used for the lithological summary was roughly 300 pounds (four 5-gallon buckets) and is believed to be a fair representation of the stockpile (rock type percentages did not fluctuate appreciably between sample bags/pails). This sample size also ensured that adequate amounts of each rock type were available for subsequent mortar bar testing and absorption and specific gravity determination, which assisted with the volume percentages reported throughout this analysis. It should be noted that the aggregates acquired for this analysis were extremely dirty. Initial efforts to obtain a fresh, clean face necessary for lithological identification were unsuccessful. This included simply spraying the particles in a lab sink to remove the black film of dust often found coating the aggregates. Only high pressure water from a pressure washer was capable of removing this film. According to Larry Zanko, geological engineer for the Natural Resources Research Institute, this material is currently not being washed at the mine nor was it washed by Ulland Bros., who crushed the stockpiled material at Mn/Road.

Some of the minerals encountered during thin section analysis are fairly unique to iron formations. Their presence has been verified by earlier studies using X-Ray analyses. Some of these iron-rich minerals, particularly minnesotaite and greenalite, form solid solutions involving substitution of magnesium and iron. For example, previous X-ray analyses suggest that talc, the magnesium-rich equivalent of minnesotaite, is present in iron formation rocks. Distinguishing the two mineral species, petrographically, can be tedious given the plethora of characteristic needles in thin section. Consequently, the reader should note that references to the presence of minerals which form solid solutions with other minerals also take into account the possible presence of end member or intermediate minerals. Additionally, several varieties of iron oxide are present in the samples, most notably magnetite but also goethite, hematite and limonite. Given the fine grained nature of most of the iron oxide minerals, distinctions between the varying types (except for magnetite) were often not made in thin section and, unless specified, will be loosely referred to as 'iron oxide' in the written analysis. Also, though siderite appears to be the prevailing carbonate mineral in the samples, previous X-ray analyses suggest that ankerite and dolomite may also be present. Nonetheless, all carbonates will be referred to as siderite unless a distinction can be made.

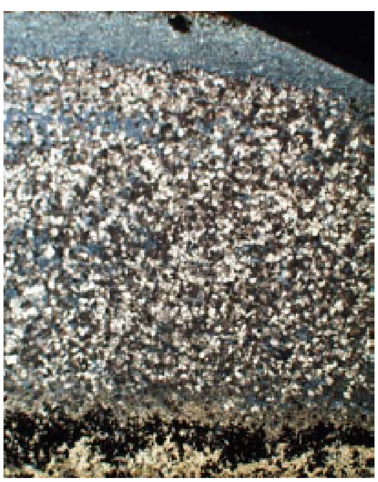

Fig. 2: Photomicrograph (10.5mm X 8mm) of an aggregate consisting of alternating beds of (starting from top) chert, chert and dolomite(?) and, magnetite with coarse siderite(?).

Given the depositional, burial and kinematic history of Minnesota's iron formation rocks, variability in rock type percentages and mineralogies will likely be encountered throughout the LC-8 ledge. Also, roughly 5% of the sample by volume consisted of aggregates with very thin, alternating beds composed of distinct mineralogies in various amounts characteristic of the *silica-rich, carbonate-rich and magnetite-rich* varieties (Fig. 2). Conversely, gradual mineralogic transitions between varying rock types were also observed in several aggregates belonging to the *silica-rich* and *carbonate-rich* classes (Fig 10).

Silica-Rich

(Siliceous Rock and Chert-Rich)

Approximately 60% of the total sample, by volume, consists of the *silica-rich* aggregate types. Though the *silica-rich* component in Minnesota's iron formations is typically referred to as 'cherty' by the mines and in publications, this group's quartz fraction is more adequately represented, texturally, by the presence of fine grained quartz. In outcrop, *silica-rich* beds are typically thicker-bedded than the *carbonate-rich* beds (Fig. 1).

'Siliceous Rock'

Approximately 55% of the total sample, by volume, consists of a siliceous rock type where quartz comprises the bulk of the mineral constituents. Two varieties of the siliceous rock type were identified and varied based on iron oxide and minnesotaite content.

Type I (ferruginous):

Roughly 46%, by volume, of the total sample are of the Type I variety. Type I aggregates are composed of a matrix of what appears to be recrystallized (with some secondary) fine-grained quartz. Chert is also present, typically in smaller quantities throughout the rock type, but does comprise the matrix in several aggregates displaying a Type I-like texture (discussed in the *Chert* section below; see also Fig. 12). Ovate nodules/ooids are visible and are composed mainly of magnetite and greenalite but also of quartz, siderite, and minnesotaite. Greenalite is also seen forming fine globules (possibly left over from replacement processes) which in turn occasionally alter to iron oxides. Iron oxide is often found as an alteration product in nodules and comprising what appears to be an insoluble byproduct in styolitic, pressure solution veins. Minnesotaite is commonly present both in the matrix and as a replacement product in the nodules. Siderite was found interspersed and in some slides appeared to favor zones where inferred pressure solution took place.

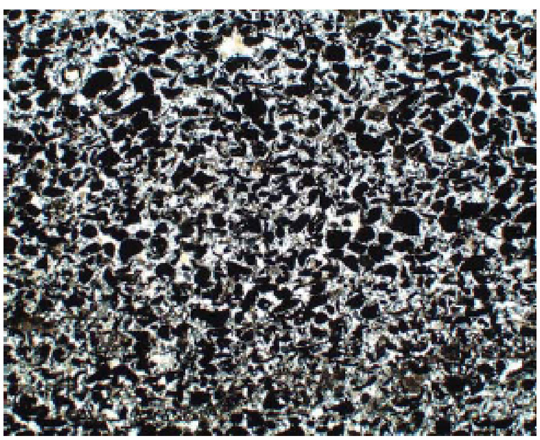

Fig. 2: Photomicrograph (crossed polars; 10.5mm X 8mm) of Type I siliceous aggregate showing high concentration of nodules.

Though little mineralogical variation is visible within Type I, distinctions can be made based on quantity of nodules within an aggregate. These differences in quantities produce textural distinctions in hand sample: aggregates that are rich in nodules are typically darker in color and have a gritty surface appearance (Fig. 2) whereas, aggregates with lower concentrations of nodules tend to have coarser nodules and higher concentrations of quartz which render the particles a lighter color (Fig 3). Additionally, the coarse nodules found in the latter variety are often visible to the

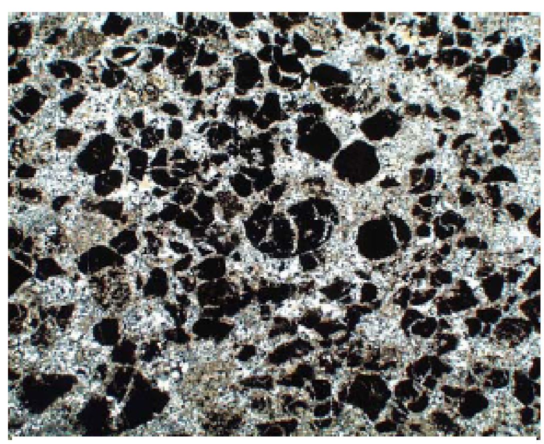

Fig. 3: Photomicrograph (crossed polars; 10.5mm X 8mm) of Type I siliceous aggregate showing low concentration but larger nodular grain size.

naked eye and a freshly fractured face has a more 'shattered glass' and 'salt and pepper' appearance. Siderite was also found mainly in aggregates with high quantities of nodules. Collectively, the dark color of the Type I aggregates is due to the presence of dark minerals such as magnetite and other iron oxides as well as greenalite found throughout the aggregates. The Type I category is comprised of roughly equal amounts, by volume, of the fine and coarse- grained varieties.

Type II (minnesotaite-rich):

Approximately 9%, by volume, of the total sample are of the Type II variety (Fig. 4). Type II aggregates share the characteristic quartz matrix found in Type I. However, preexisting nodules are now composed almost exclusively of minnesotaite (Fig. 5). Occasionally some nodules composed of iron oxides (and occasionally siderite and greenalite) can be seen, but overall the mineral variation seen in Type I is scant to nonexistent in Type II. No distinction was made in quantity of 'nodules/ooids' now composed of minnesotaite, though one could probably be made since Type II varieties appear to be minnesotaite-rich varieties of Type I. In hand sample, the dominance of minnesotaite rendered the aggregate a light green color.

Fig. 4: Photomicrograph (crossed polars; 10.5mm X 8mm) of a minnesotaite-rich aggregate. Minnesotaite-rich areas are tan in color.

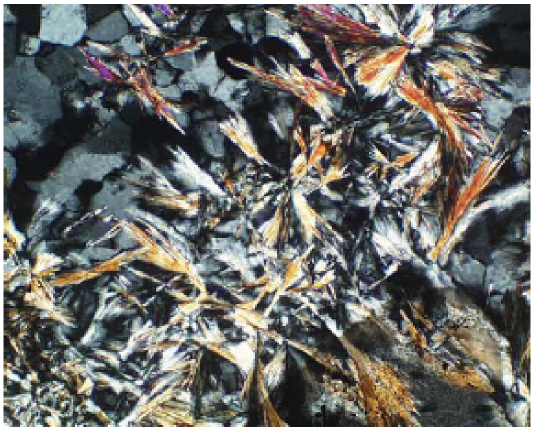

Fig 5: Photomicrograph (crossed polars 0.8mm X 1.1mm) of radiating minnesotaite crystals.

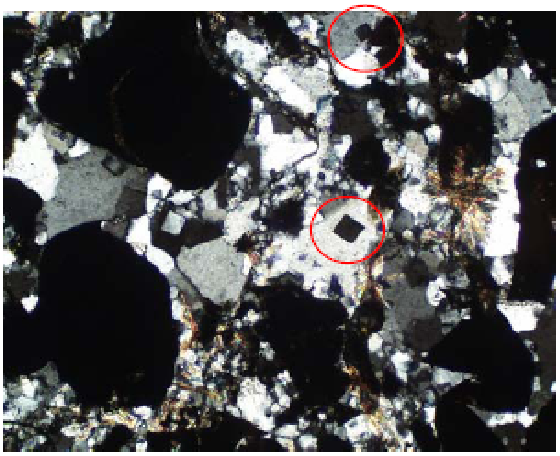

Fig.6 : Photomicrograph (crossed polars; 2mm X 2.8mm) of Type I aggregate. Rhomb-shaped crystals (circled), now composed of quartz, are visible in the matrix and are likely pseudomorphs after siderite or dolomite.

Observations:

In both of the above-mentioned siliceous varieties, evidence of low-grade metamorphism or burial deformation is visible. In the quartz matrix, remnants of recrystallization appear to be present and may have been accomplished by grain boundary migration (GBM). In some slides, vestiges of a preexisting matrix are present and similar to Type I-like chert aggregates (discussed in *Chert* section below) consisting of a chert matrix with interspersed siderite/dolomite crystals (Fig.6). Some 'left-over grains' from recrystallization appear to be visible in both types but are probably more prevalent in

Type I aggregates. Though GBM typically occurs at medium to high grade conditions, the presence of phylosilicate minerals (minnesotaite/talc) and styolitic, pressure solution veins (Fig. 7) coupled with the lack of higher grade fabrics suggests a lower grade environment (GBM can be accomplished during low-grade deformation if high pore water pressures are present within the rock). Relict fractures are also preserved in both aggregate types.

Pseudomorphism is also visible in the siliceous aggregates and is likely a result of either metamorphic or burial processes. Most replacement is performed by fine-grained quartz but is also accomplished by minnesotaite, magnetite and chert. Quartz is found replacing both primary and secondary minerals. Whole nodules are often replaced by quartz and, occasionally, a thin iron oxide shell is visible around nodules detailing the original shape of the preexisting nodule. Quartz is also present forming serrated to blocky reaction rims or moats, around unreplaced nodules (Fig.8). Compared to the colorless quartz matrix, this secondary quartz is typically discolored to a light yellowish-brown color and occasionally, dark brown with a physically 'dehydrated' appearance. Some pseudomorphic quartz crystals even appear to have acquired a rotating, 'iron-cross' extinction pattern upon replacement of either minnesotaite or possibly recrystallization from chalcedony (Fig. 9). Occasionally quartz is found structurally mimicking the coxcomb and rhombohedral arrangement of preexisting siderite. Very fine residual iron oxide from replacement of siderite and greenalite with fine-grained quartz may explain some of the yellowish-brown to brown discoloration often seen in the siliceous rock types. Replacement with fine grained quartz appears to have been accomplished through several sequences: 1) greenalite to quartz, 2) siderite to quartz, 3) minnesotaite to quartz, 4) magnetite to chert?, 5) incomplete replacement of greenalite to quartz, spheroid or hexagaonal crystal allowing growth of minnesotaite around greenalite core

Fig. 7: Photomicrograph (plain light; 10.5mm X 8mm) of a pressure solution vein.

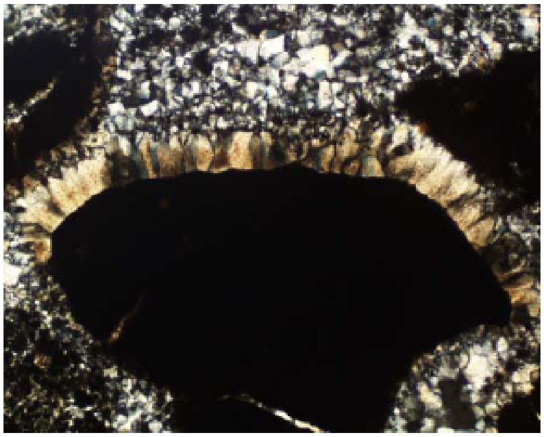

Fig. 8: Photomicrograph (crossed polars; 2mm X 2.8mm) of nodule with light-yellowish brown secondary quartz reaction rim.

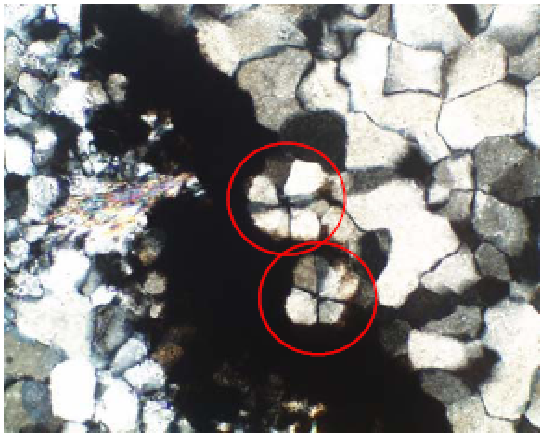

Fig. 9: Photomicrograph (crossed polars; 0.8mm X 1.1mm) of either recrystallized quartz from chalcedony or quartz after minnesotaite (circled). Pseudomorphs retain the rotating extinction pattern.

(core sometimes alters to iron oxide) which, in turn, allows replacement of radiating minnesotaite with quartz.

Though nodule concentrations likely varied within the siliceous beds prior to burial or low-grade deformation, the variable quartz contents now found in some Type I aggregates may be partly due to the differing degrees of quartz replacement.

Magnetite is also visible as a secondary mineral in nodules forming euhedral crystals after greenalite. Fine grained, euhedral magnetite also appears to fill void space or possibly replace preexisting minerals in siderite-rich beds. An anhedral, fine grained form of magnetite (primary?) is also visible in the cores of several nodules in Type I aggregates and, in reflected light, appears to have been preserved from complete replacement by or alteration to some sort of iron oxide or secondary magnetite.

As mentioned, minnesotaite is found in both siliceous varieties. However, minnesotaite is found almost exclusively in the Type II aggregates where it is found in zones previously occupied by nodules, former pressure solution veins, the shells encompassing nodules, and in areas where greenalite globules altered to iron oxide. Though minnesotaite appears to replace some minerals, specifically greenalite, the above data seem to suggest that minnesotaite growth was favored in zones where alteration products, iron oxides, were present.

To sum up, Type II varieties appear, texturally, to be minnesotaite-rich varieties of Type I. In hand sample and in thin section some aggregates displayed mineralogic characteristics of both the Type I and Type II varieties. One thin section showed mineralogies which transitioned from Type I to Type II (Fig. 10). These types of assemblages made distinction between the two varieties difficult at times. A category acknowledging these gradational aggregate species was not made-aggregates were, thus, grouped based on dominant mineralogy. Overall, it is apparent that deformation rates or burial conditions varied within the ledge owing to the gradation in *silica-rich* varieties.

Fig. 10: Photomicrograph (crossed polars; 10.5mm X 8mm) of aggregate displaying a transition (top to bottom) from Type I mineralogy to Type II mineralogy.

Fig.11: Photomicrograph (crossed polars; 10.5mm X 8mm) of a chert aggregate. Minnesotaite crystals are concentrated in the upper third of the slide, euhedral siderite/dolomite crystals are visible in the lower half of the slide, and coarse carbonate is present in a wedge on the right fringe of the particle.

Chert-Rich

Between 5 and 10% of the total sample, by volume, consists of *chert-rich* aggregate which is typically black to light green and displays a conchoidal fracture and sharp fractured edges in hand sample. In one thin section, the matrix is characterized by a cherty texture with indistinguishable quartz 'grains' encompassing radiating minnesotaite fibers, euhedral crystals of pleochroic siderite/dolomite and zones of coarse grained carbonate and fine-grained, secondary quartz (Fig. 11). Some chalcedony can also be found. Light green chert varieties are present and likely contain higher minnesotaite concentrations whereas black varieties likely consist of higher quantities of iron oxides.

As mentioned in the Type I description, several chert-rich aggregates similar to the coarse-grained variety of Type I were identified during litho-picking (Fig.12). In hand sample, the particles are very similar texturally to Type I but have a more conchoidal fracture, glassy appearance and sharper edges. In thin section, a chert matrix is prevalent as are the characteristic nodules, with several appearing to be partially or wholly replaced by chert. Euhedral siderite was commonly found scattered throughout this aggregate type in thin section; reflective siderite crystal faces can often be seen in hand sample. Minnesotaite is also commonly found in this aggregate type.

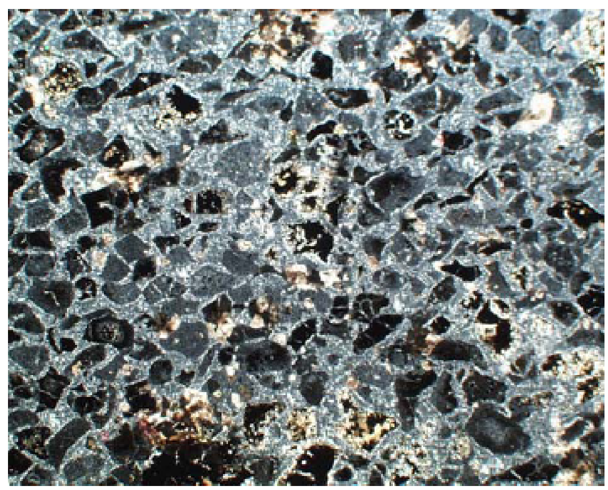

Fig.12 : Photomicrograph (crossed polars; 10.5mm X 8mm) of Type 1-like aggregate with chert matrix. Some replacement of nodules by chert is visible (light-colored areas). Tan-colored crystals are siderite.

Some chert-rich aggregates contained an anomolously soft, black material possessing conchoidal fracture and concentrated in nodular, pea-sized zones. Personnel from the Minnesota Geological Survey speculated that this component may be composed of an asphaltite mineral termed anthraxolite. According to texts, anthraxolite is essentially the crystalline remains of preexisting hydrocarbons and has purportedly been identified in iron formation rocks in Minnesota. Apparently, asphaltite minerals will typically ignite upon exposure to intense open flame. No attempt, however was made to ignite this material since the small amount available was needed for verification via infrared analysis. The analysis, performed by the MN/DOT Chemistry Unit, did confirm that a small fraction of aromatic carbon chains are present.

Carbonate-Rich

Siderite-Rich, Cherty Siderite, and Meta-Siderite-Rich

Approximately 30% of the total sample, by volume, consists of the *carbonate-rich* aggregate types. In hand sample the aggregates range from black to dark brown to light brown, are mostly fine grained and, based on the shape of the aggregates, appear to have been derived from thin beds within the ledge (see Fig. 1). Though composed mostly of carbonates, ledges and members of this rock type are commonly referred to as 'slaty' by the mines or in publications. In thin section, the aggregates often display a faint bedding or foliation which becomes manifested in hand sample by parallel top and bottom bedding planes. Often a black, fine-grained but robust, film that sometimes appears slickensided is found coating some surfaces of this aggregate type and possibly delineates the *carbonate-rich* rocks into thin beds (this film has also been observed in the siliceous varieties and other rock types within the sample). The quartz/chert content can also vary considerably within this aggregate type and governs the hardness.

Siderite-Rich and Cherty Siderite

Approximately 19% of the total sample, by volume, consists of *siderite-rich* aggregate. In thin section, the *siderite-rich* mineral assemblage is dominated by siderite, stilpnomelane and iron oxides (Fig. 13). Siderite is mostly found as fine-grained, anhedral aggregates. In some thin sections, the siderite minerals are coarser grained and display a faint 'willow leaf' to slender rhombohedral crystal shape. Many siderite crystals contain pleochroic patches which may be due to crystal orientation or alteration to iron oxide, particularly goethite. Siderite is typically found associated with stilpnomelane crystals and often encapsulated by a film of iron oxide (possibly goethite). Stilpnomelane is present as very fine grained, radiating to sheaf-like aggregates. Occasionally, it is found as coarse crystals in or around iron oxide-rich styolitic veins or replacing/altering to scattered 'pockets' of a green mineral- greenalite, but possibly Al-bearing chamosite. Minor minnesotaite and greenalite/chamosite, as just mentioned, is also present in variable quantities. Fine grained quartz is also found in minor quantities disseminated throughout the aggregate or in bands which sometimes accentuate a faint foliation or bedding.

Fig. 13: Photomicrograph (crossed polars; 10.5mm X 8mm) of siderite-rich aggregate. Bbrown areas are composed mainly of siderite and clear to white zones are quartz/chert.

Fig. 14: Photomicrograph (crossed polars; 10.5mm X 8mm) of cherty siderite. Though grains are indistinguishable, the mass has a greyish hue in thin section from the high concentration of chert.

Approximately 9% of the total sample, by volume, consists of *cherty siderite* aggregate. In hand sample, the *cherty siderite* aggregates are texturally identical to the *siderite-rich* aggregates (Fig. 14). In thin section, however, they are composed of very fine-grained siderite and chert which varies from equal amounts of siderite and chert to increasingly greater amounts of chert. Minnesotaite, as opposed to stilpnomelane, is commonly found throughout the aggregates as very fine-grained needles. Several aggregates were found to be composed of coarser-grained siderite with a chert matrix which, in hand sample, made them deceptively similar to the fine-grained version of the Type I, silica-rich aggregates. Also, some aggregates were almost completely dominated by chert with interspersed iron-oxide 'fish', which possess a preferred grain shape orientation. This variant may represent a more deformed equivalent of the *cherty siderites* and given its mineralogic composition could be more aptly classified as chert. Because of the higher quartz/chert content, *cherty siderite* aggregates are harder than their *siderite-rich* counterparts and display a more angular conchoidal fracture in hand sample.

Observations

As seen in the siliceous rocks, remnants of weak/low grade metamorphism or burial deformation appear to be present. Pressure solution appears to have taken place resulting in the formation of scattered iron oxide-rich, styolitic veins which parallel the top and bottom faces of the aggregate. A dark halo of concentrated iron oxide is sometimes present near these styolitic veins which grade into lower, less dark iron oxide concentrations where iron oxide is typically found encompassing just siderite grains. It is possible that a portion of the iron oxide found in this rock type may have been produced via alteration of siderite during deformation or burial.

In regards to the 'film' found coating many of the *carbonate-rich* aggregates, petrographic analysis was not sufficient in determining its chemical make-up. In thin section, the film appears as a fine grained, finely-laminated opaque material, most likely composed of indistinguishable iron oxides, which are often interlayered with bands of siderite, stilpnomelane and serrated and deformed quartz. It seems plausible, given the presence of pressure solution visible in several siderite-rich aggregates, that the 'film' found on many aggregates is a product of focused deformation along more soluble or weaker zones within the siderite-rich beds.

Given the presence of iron carbonate in the sample, an insoluble residue was performed on a 100g sample comprised of randomly selected siderite-rich aggregates to obtain an estimate of percent-soluble. Testing initially revealed that 50% by mass was soluble with several 1/4"-sized aggregates still present at the conclusion of testing. Further crushing of the remaining insoluble portion and subsequent testing revealed a final total of 70% soluble by mass. Complete dissolution of all siderite grains during the first phase of testing was probably not achieved due to the presence of iron oxides and stilpnomelane coating siderite grains, as seen in thin section. Since no attempt was made to measure the amount of soluble iron in solution, a reliable measurement of soluble carbonate could not be acquired. Additionally, the soluble fraction of the test rendered the solution a green color suggesting that a copper, nickel or chromium component may be present in the aggregates.

Meta-Siderite-Rich

Approximately 2% of the total sample, by volume, consists of a coarse-grained, foliated aggregate dominated by siderite. In both hand sample and thin section, siderite is noticeably coarser-grained (from recrystallization) than the previously-mentioned *carbonate-rich* varieties and displays a preferred grain shape orientation responsible for the visible foliation (Fig 15.). Stilpnomelane is scattered throughout in pockets which are bounded by ribbonized siderite. Like the previously-mentioned siderite-rich aggregates, quartz/chert and greenalite/chamosite are also visible but coarser grained.

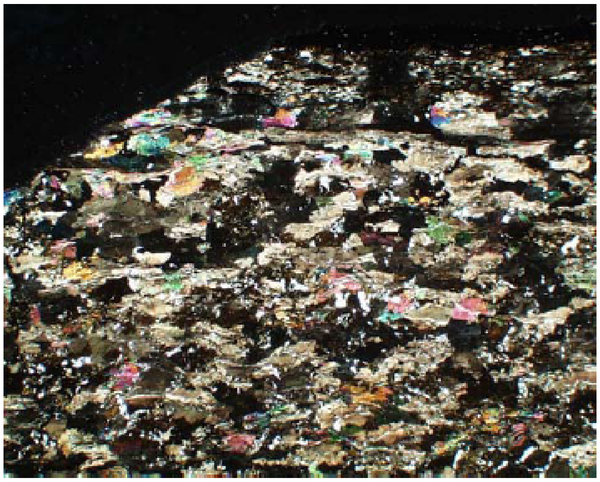

Fig. 15: Photomicrograph (crossed polars; 10.5mm X 8mm) of a meta-siderite-rich aggregate. Tan and multi-colored zones are composed of coarse-grained siderite. Black-colored zones are also composed of coarse-grained siderite but appears extinct.

Evidence of deformation is present throughout the aggregate type. In one slide, lattice preferred orientation is visible in a thin bed of fine grained stilpnomelane and is manifested by uniform parallel extinction. Siderite can also be seen as inclusion patterns growing into preexisting pressure solution veins. Pure shear sense indicators are also present particularly in the pseudomorphic quartz fraction where preexisting nodules, as well as the accompanying quartz grains, now display a flattened shape.

Magnetite-Rich

Approximately 5 to 10% of the total sample, by volume, consists of magnetite-rich aggregates. In hand sample, these aggregates are noticeably heavier than the other aggregate types and variably magnetic. The aggregate type often has a metallic appearance due to the presence of magnetite which is visible in thin layers as consolidated, euhedral crystals or is disseminated, but concentrated, throughout the aggregate. In one thin section, stilpnomelane, greenalite, siderite, calcite, hematite and other iron oxides are all visible (Fig 16).

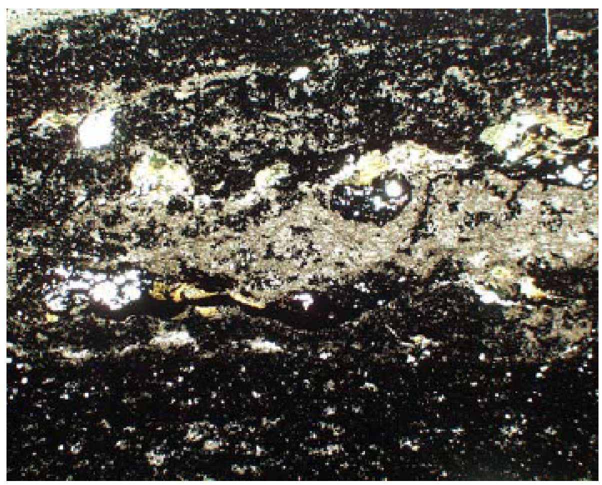

Fig. 16: Photomicrograph (crossed polars; 2mm X 2.8mm) of a portion of magnetite-rich aggregate. Black zones are magnetite. Tan-colored zones are composed of siderite.

Based on hand sample examinations it appears that magnetite-rich aggregates are essentially iron-rich varieties of the previously mentioned *silica-rich* and *carbonate-rich* rock types. The *silica-rich* aggregates appear to comprise the bulk of the *magnetite-rich* varieties with lesser amounts distributed proportionally amongst the other varieties.

Many of the silica-rich aggregates contain one or more small bands or layers composed of a dusky, fine grained material found at the tops, bottoms or within the aggregates. The bands are strikingly similar to those found in magnetite-rich aggregates which contain metallic, magnetic magnetite. It is possible that these silica-rich aggregates with nonmagnetic bands contain an altered, but still iron-rich, form of the previously magnetic magnetite bands.

cc: Doug Schwartz, Glenn Engstrom,
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