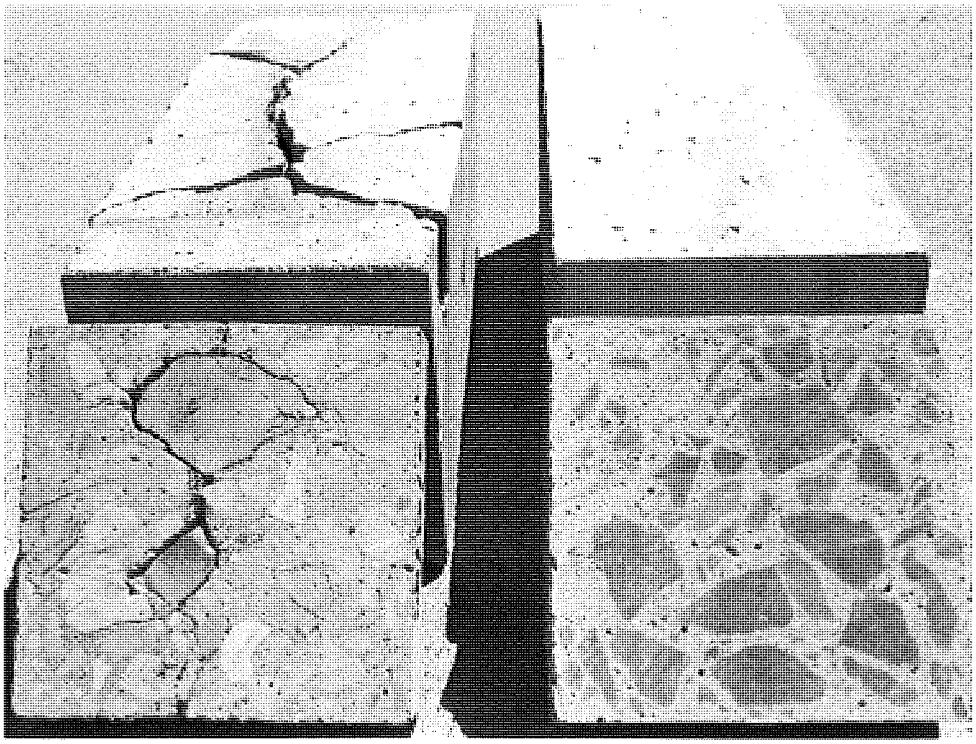
MDOT Research Report RC-1452

Freeze-Thaw Evaluation of Large Coarse Aggregate Using MDOT's Confined and Unconfined Methods



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16. Abstract
MDOT has been considering using freeze-thaw (F-T) resistant 2.5 in. nominal maximum size aggregate in concrete pavement mixes to gain benefits associated with improved joint/crack performance and lower paste volume without sacrificing freeze-thaw durability. This study investigated the potential for correlating F-T results from MDOT's Series 6 (1 inch nominal maximum size) coarse aggregate gradation with a large aggregate gradation containing a 2.5 in. maximum size. A variety of investigative techniques including visual assessment, confined and unconfined F-T testing, micro-porosity evaluation, and low temperature dilatometry were used in this study. Based on this investigation specific conclusions and recommendations were made to MDOT regarding: large aggregate F-T properties, test methods, identifying coarse aggregate with D-cracking characteristics, the increased risk of F-T failure of inhomogeneous large aggregate sources, the low risk of F-T failure in homogeneous large aggregate blends of low absorption capacity (<1%).

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Final Report

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ACKNOWLEDGEMENT

The research team would like to thank the Michigan Department of Transportation (MDOT) Technical Advisory Group (TAG) members for their help in making this a joint UM-MDOT report. Thanks also to Dr. Gail Grove, U of M Assistant Research Scientist, for his guidance and help in the initial phase of the project. Both undergraduate and graduate students were involved in preparing the aggregates and helped in making the F-T beams. Their contribution is greatly acknowledged.

DISCLAIMER

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

BACKGROUND

Standard MDOT specifications for Portland Cement Concrete (PCC) Series 6 coarse aggregate (CA) provide for a maximum size of 1 inch. Coarse aggregate gradations for PCC, that include larger maximum sizes were discontinued by MDOT in the 1960's in order to improve concrete freeze-thaw (F-T) durability. At approximately the same time the Series 6 gradation was adopted (1 inch maximum size) for most concrete grades, and F-T durability testing and specifications were instituted for all CA sources used in PCC. Overall F-T durability was improved by the change to a reduced maximum size CA gradation, but certain beneficial properties of larger maximum size gradations were lost. Studies indicate that reduced aggregate size improves F-T durability for a given source, but the attribute of load transfer across cracks is diminished. In short, as the CA maximum size becomes smaller, the narrower a crack must be for aggregate interlock to provide load transfer.

Reduced coarse aggregate maximum size usually necessitates higher cementitious content to achieve a specified compressive strength. Greater cement content increases potential for some of the negative affects high cement content can have on concrete durability.

Ideally, MDOT seeks to regain the benefits of using larger maximum sized CA in concrete mixes, without sacrificing long term F-T durability.

OBJECTIVES

Test ten sources of quarried CA employing the MDOT Michigan Test Methods (MTM) for confined and unconfined F-T testing. Two gradations were tested, the standard Series 6 gradation CA, and then a test gradation that includes 2.5 inch maximum size particles.

Examine, and conduct other appropriate tests on specimens in an effort to understand reasons for the varying durability of CA sources and types.

Determine the relationship, if any, between the smaller and larger gradations and the confined and unconfined F-T test results. Study the relationship between 1 inch maximum sized aggregate and 2.5 inch aggregate when tested using MDOT's unconfined F-T test.

Determine if a transfer function can be adopted that provides MDOT a way to predict the relative durability of 2.5 inch material from data collected as part of MDOT's existing Series 6 F-T testing program.

Begin the development of a list of quarried aggregate sources that may be used for 2.5 inch maximum sized gradations without causing long term F-T durability problems.

Begin the development of a list of aggregate sources that have acceptable F-T durability only up to 1 inch maximum size.

PROJECT DATA COLLECTION AND REPORT HISTORY

Prospective aggregates sources for this study were contacted by mail in October 1997. All the prospective sources of CA that were contacted, expressed an interest in participating in the study.

The first formal meeting of TAG group was held on 11-13-97 for the purpose of planning scheduling. At least four additional planning meetings were held between selected TAG members and the U of M investigators in December 1997 and January 1998.

Sampling of CA from the selected sources commenced in December of 1997. Sampling continued in the spring and fall of 1998 as U of M was able to process the large samples required, and storage space became available. The last CA sources were sampled in the spring and summer of 1999.

Purchasing of supplies and equipment began, and the first of a series of technicians was hired by
U of M, in January 1998.

A "kick-off" meeting of the full TAG and U of M investigators was held on February 9th 1998.
Many meetings and other contacts between the principle investigators and various TAG members continued throughout the life of the project.

The laboratories at MDOT (Series 6 testing) and U of M (Large Gradation testing) collected confined freeze-thaw test data first. They accomplished preliminary work, batched concrete, and fabricated test specimens as equipment and personnel availability permitted.

Confined and Unconfined F-T testing at the MDOT laboratory was completed and reported to the principle investigator on 11-23-99. The U of M completed confined testing early in the year 2000. Unconfined F-T testing was completed at the U of M the first week of April, 2000.

Petrographic analysis was performed at the U of M and involved many observations and types of tests. Individual aggregate particles, as well as concrete beams used in the confined testing phase of the study, were analyzed. Other tests performed as part of the overall petrographic analysis included low temperature dilatometer, which continuously determines the aggregate micro-strain versus temperature relationship during a F-T cycle.

The first complete draft of the final report was dated and received on October, 19th 2000. Members of the TAG reviewed the draft report and met with the principle investigator in early December of 2000 to provide feedback including corrections and possible revisions. Further meetings were held in 2001 at the MDOT laboratory in Lansing and at the U of M in Ann Arbor.

The second revised draft final report was submitted by the principle investigator to the TAG on January 30th, 2002. After reviewing the revised draft, the members of the TAG met with the principle investigator in the third quarter of fiscal 2002 for the purpose of discussing further corrections and edits to the report.

The third revised draft final report was submitted by the principle investigator on December 9th, 2002. The final report was completed during the summer of 2004.

KEY PROJECT FINDINGS

- Based on the data collected in this study, a single transfer function to predict the durability of large sized aggregate from test results collected as part of MDOT's ongoing Series 6 aggregate testing program is not possible. The reason for this was the widely different F-T response. Some aggregate sources had near zero F-T expansion at any size while other aggregate sources had different F-T behaviors as the aggregate size increased. Although the aggregate sub-categories were found to exhibit substantial differences in expansion upon freezing, these differences were not controlled only by absorption capacity or relative micro-porosity. Other factors such as shaley bedded layers, mottling and micro-cracks developed during aggregate processing can contribute to poor F-T performance.

- The sources of aggregate tested in this study seemed to fall into three durability categories. These categories are: (1) high beam expansion and aggregate mass-loss, (2) medium beam expansion and aggregate mass-loss and (3) low beam expansion and aggregate mass-loss. Only high quality coarse aggregate belonging to category 3 were found to be F-T resistant irrespective of maximum particle size. Three of the ten sources were found in this category. Category 1 coarse aggregate were found to have D-cracking characteristics. The large aggregate F-T beams from these sources developed cracks after only a few cycles. Visual examination of these beams after testing showed substantial mortar cracking caused by subtypes of large particles and internal aggregate cracking. The visual observations are consistent with high aggregate dilation during freezing of pore water and a permanent increase in length after one F-T cycle due to internal aggregate damage. Unconfined mass-loss tests show that these sources have a 10 fold increase in mass-loss between the Series 6 and the large aggregate blend. These findings are consistent with beam expansion results which show a much larger expansion for the Series 4 aggregate blend than the Series 6 coarse aggregate. Three coarse aggregate sources were found in this category.

- Aggregate belonging to group 2 with moderate F-T resistance in Series 6 were found to develop greater F-T damage in the larger size, thus exceeding the current MDOT threshold for pavement concrete. Source inhomogeneity within the moderate F-T category is a major risk factor when increasing the top size from 1 inch to 2.5 inches. The Dolomite 5 source contained several different aggregate subtypes of widely different expansion upon freezing and porosity (absorption) characteristics. The results from this investigation suggest that the aggregate subtypes with greatest expansion due to freezing of pore water dominate the concrete F-T resistance, which in turn results in poor F-T performance in large aggregate blends. If such large size aggregates are used for a given project, even a small increase in the percentage of an aggregate subtype with high expansion, absorption and micro-porosity may significantly reduce F-T performance.

- Most coarse aggregate sources available for Portland cement concrete (PCC) in Michigan are in the Moderate F-T category (group 2). Confined testing and consistent monitoring is required even for Series 6 material in this category. Large maximum size aggregate from sources in this category should not be used in exposed PCC without qualifying them with additional confined F-T testing, and without consistent field monitoring.
- A list of frost resistant 2.5 inch maximum sized quarried aggregate sources was instituted by MDOT as a result of this study. Three sources of coarse aggregate in this study were judged to be durable up to 2.5 inch maximum size in exposed concrete.

- Coarse Aggregate Freeze-Thaw durability rating, using confined Freeze-Thaw testing according to (MTM) 113, 114 and 115 should be continued for Series 6 gradation. Any future rapid test procedure to evaluate F-T resistance should be correlated with the existing test method. Future correlations may be appropriate between the existing confined freeze-thaw test for series 6 coarse aggregate and the current coarse aggregate unconfined test modified for moisture conditioning as specified in MTM 113.

- Neither visual inspection nor absorption capacity value for the aggregate provides definitive answers with respect to F-T resistance. Developing a rapid test procedure based on a single F-T cycle of the aggregate in a confined or unconfined condition, which determines the specimen dilation (micro-strain) associated with freezing of pore water, is recommended.

- No coarse aggregate F-T test program can specifically predict the life expectancy of pavements. Material related F-T failure is only one mechanism of failure. Field conditions, pavement design, construction practice, loading, etc, play important roles in the overall durability of pavement. However, F-T related deterioration of joints and cracks and poor aggregate interlock are failure mechanisms in concrete that can be greatly minimized or eliminated as a concern if high quality large coarse aggregate is used.

CHAPTER 1 - INTRODUCTION

1.1 Background and Problem Statement

Since the early to mid 1960's, large size (1½ to 2 inch) coarse aggregate has not been used in the Michigan Department of Transportation (MDOT) standard concrete mixes due to the potential for freeze-thaw problems such as D-cracking, popouts and associated joint failures caused by non-durable aggregate types. D-cracking is the freeze-thaw (F-T) deterioration of susceptible coarse aggregate particles in the concrete. D-cracking susceptible coarse aggregate in a critically saturated condition dilate as they freeze causing internal aggregate damage. If confined in concrete, the aggregate dilation causes cracking in the surrounding mortar. Key aggregate properties, which determine the D-cracking susceptibility, are pore structure, absorption capacity, size and aggregate type (limestone, dolomite, chert). Reducing the nominal maximum size is the single most effective way to improve F-T resistance of concrete containing D-cracking susceptible aggregate [1-4].

It was initially thought that overall field performance of concrete pavements had also improved. Over the years, it was discovered that due to this change other challenges arose. Elimination of large size coarse aggregate in the mixes required increased cement content, which in turn increased problems such as thermal dilation and drying shrinkage. Additionally, when aggregate size was reduced aggregate interlock also decreased. Recently, MDOT has been considering using F-T resistant 2½ inch nominal maximum size aggregate in their concrete mix designs in order to regain the benefits associated with improved aggregate interlock, and a lower paste volume without sacrificing freeze-thaw durability.

In this project, the testing of Michigan Series 6 with blended 2½ inch maximum size aggregate will be performed according to MDOT Michigan Test Methods (MTM) for confined (MTM 113, 114 and 115) and unconfined (MTM 124) coarse aggregate F-T testing [5-8]. In addition, the mechanisms of F-T deterioration will be investigated through unconfined dilation during freezing of coarse aggregates.

1.2 Project Objectives

The primary objective of this study is to determine if a simple transfer function can be obtained from the test data derived from the F-T testing of concrete beams containing Michigan Series 6, and the blended aggregate gradations. Then, dilation ratings for gradations containing 1½ and 2 inch material can be estimated from the Michigan Series 6 test results using the transfer function. The MDOT and University of Michigan (U of M) laboratories performed F-T testing on ten sources of coarse aggregate including quarried limestone, dolomite and trap rock. The MDOT confined and unconfined test methods were used. MDOT performed F-T tests on the Michigan Series 6 coarse aggregate gradation and U of M performed the freeze-thaw tests on the blended gradation that included Michigan Series 6 with 1½ and 2 inch material from the same source.

1.3 Research Plan

Ten coarse aggregate sources were selected for these reasons: (1) sources were chosen that may supply large quantities of larger maximum size coarse aggregate; (2) they represent a cross-section of known F-T durability based on years of testing by MDOT on standard Series 6 coarse aggregate; (3) all are from quarried sources and thus provide a more homogeneous material than gravel sources for this study.

In Phase 1 of this study, freeze-thaw dilation test results were obtained using MTM 113, 114, 115 as modified for testing a coarse aggregate gradation that includes 1½ and 2 inch particles. Test specimen size was increased for concrete containing the larger aggregate gradation (6 inch by 6 inch cross section) versus standard Michigan Series 6 beams (3 inch by 4 inch cross section). Some mix specifications were also modified. Beams were tested during freeze-thaw cycling for dilation and examined after freeze-thaw testing for cracking.

Unconfined freeze-thaw testing of both the Michigan Series 6 and the 1½ and 2 inch coarse aggregate was performed in Phase 2.

Data were analyzed in Phase 3 for the transfer function. Additional tests were conducted on the coarse aggregate to investigate the F-T mechanisms responsible for the cracking of the concrete beams in the confined F-T test. These tests included petrographic evaluations of confined and unconfined test specimens.

1.4. MDOT Technical Advisory Group (TAG)

The sponsoring agent, MDOT, formed an internal technical advisory group. The group members were:

Thomas B. Woodhouse (TAG Chair)
Douglas E. Branch
Robert W. Muethel
Alan C. Robords
David L. Smiley
John F. Staton

1.5. Report Organization

This report consists of nine chapters. Chapter 1 contains the study background. Chapter 2 presents the test methods. Chapters 3 through 6 present the study results. Chapter 7 contains data analysis for transfer function. Chapter 8 presents study conclusions and recommendations. Chapter 9 contains selected references.

CHAPTER 2 - RESEARCH METHODS

The following sections provide descriptions of the methods used for producing and testing freeze-thaw (F-T) beams containing large size coarse aggregate. This includes fresh concrete testing, unconfined and confined F-T testing, strength testing, and petrographic evaluation of the coarse aggregate sources before and after F-T testing.

2.1 Freeze-Thaw Mix Design Parameters for Large Coarse Aggregate Blends

2.1.1 Gradation of Blended Coarse Aggregate

The following background information is provided by Dr. Gail Grove, U of M Assistant Research Scientist, regarding the factors involved in arriving at a proper coarse aggregate gradation that (1) will produce concrete that will not segregate during handling, and (2) will be practical for aggregate producers to produce or stockpile. The field concrete containing coarse aggregate with nominal maximum size of 2 to 2½ inch will probably contain either a blend of two standard coarse aggregate sizes or contain a new single gradation covering the entire range of coarse aggregate (i.e. No. 4 to 2½ inch sieve size). Table 2.1.1 compares three gradations taken from the MDOT Standard Specifications (4AA 1996) and AASHTO Specifications (#3 and #4.)

Table 2.1.1 Standard Gradations (Cumulative Percent Passing)

Sieve Size (inch)	2½	2	1½	1	¾	½	⅜	No. 4
4AA	--	100	90-100	20-55	0-15	--	0-5	--
#3	100	90-100	35-70	0-15	--	0-5	--	--
#4	--	100	90-100	20-55	0-15	--	0-5	--

At the onset of this project, the final selection for a production gradation was unknown. The selection of the test gradation for laboratory evaluation of coarse aggregate F-T characteristics in confined condition was based on a 0.45 power chart which is shown in Table 2.1.2.

Table 2.1.2 Standard Gradations (Cumulative Percent Retained)

Sieve Size (inch)	2½	2	1½	1	¾	½	⅜	No. 4
4AA	0	0	0-10	45-80	85-100	92-100	95-100	100
#3	0	0-10	30-65	85-100	88-100	95-100	100	100
#4	0	0	0-10	45-80	85-100	90-100	95-100	100

Based on this table, the final selection criteria for ranking the large coarse aggregate sources in F-T were based on two factors: (1) each F-T mix should contain enough 2 inch material that some appear in each F-T beam, and (2) about 50% of the coarse aggregate gradation should be retained on the 1 inch, and above. Table 2.1.3 shows the selected test gradation for the large aggregate blend and Series 6 used in this study.

Table 2.1.3 Selected F-T Test Gradation for Study (Cumulative Percent Retained).

Sieve Size (inch)	2	1½	1	¾	½	⅜	No. 4
Large Aggregate Blend	10	20	20	15	15	10	10
Series 6	--	--	--	25	25	25	25

2.1.2 Air Content in Fresh Concrete

Total air content for concrete containing 2 inch nominal maximum size coarse aggregate should be reduced from that of the MTM standard 1 inch nominal maximum size concrete (7% +2/-1%) to 6% +1%/-1%

2.1.3 Workability Factor (b/b_0).

The coarse aggregate content, also known as the workability factor (b/b_0), is the unit volume of coarse aggregate per unit volume of concrete. The coarse aggregate content is a function of many variables such as water content, aggregate top-size, gradation, shape, and texture.

MDOT mix proportioning uses the mortar-void method based on dry loose density of coarse aggregate. Work by Talbot and Richart [9] in 1923 on mortar-void mix proportions, demonstrated that the coarse aggregate measured by dry loose volume was nine-tenths as much as obtained by the rodded method. A dry loose (b/b_0) value of 0.80 was selected for the 2 inch maximum size coarse aggregate based on a fineness modulus (FM) of 2.75 for the standard fine aggregate, Class 2NS. The fine aggregate used throughout this study is from MDOT source number, 19-58. It has a FM of 2.76, absorption of 1.30%, and bulk-dry specific gravity (BSG) of 2.62.

2.1.4 Key Mix Parameters

The MDOT mortar-void mix proportions used in this study were targeted for use with fine aggregate with a fineness modulus of 2.75. The mix design parameters and their target values are listed in Table 2.1.4 for the Series 6 and the large coarse aggregate blend.

Table 2.1.4 Mix Design Parameters and Target Levels

Parameters	Series 6	Large Coarse Aggregate Blend
Cement Content	517 lbs/cyd	517 lbs/cyd
Relative Water Content	1.15	1.15
Slump	2-3 inches	2-3 inches
Air Content	7 % (+2.0/-1.0)	6 % (+1/-1)
Coarse Aggregate Unit Volume (b/b_0)	0.75	0.80

2.1.5 Twenty Four Hour Vacuum Saturation of Coarse Aggregate

The coarse aggregate is oven dried, then vacuum saturated according to MTM 113. In this procedure, the dried aggregate is brought to a vacuum of 28.5 ± 0.2 inches of mercury for one hour before water enters the chamber from the bottom while maintaining vacuum. The vacuum is released after the chamber is full and soaking continues for another twenty three hours.

The fine aggregates were brought to a uniform moisture condition greater than the absorption two days prior to mixing. The moisture content was determined on the day of mixing.

2.2 Aggregate and Fresh Concrete Properties

2.2.1 Aggregate Specific Gravity and Density

The coarse aggregate properties of the large size blend were determined on gradations conforming to the selected gradation listed in Table 2.1.3. The bulk specific gravity and absorption of the coarse aggregate were determined according to ASTM C 127 "Standard Test Method for Specific Gravity and Absorption of Coarse Aggregate." In this test method, the aggregate sample is immersed in water for 24 hours. In addition, the aggregate properties were determined after the aggregate sample had been vacuum saturated (MTM 113). The coarse aggregate oven dry loose density was determined as prescribed in MTM 113 and according to ASTM C 29 "Standard Test Method for Density and Voids in Aggregate" using the shoveling method.

The properties of the fine aggregate, specific gravity and absorption, were determined by MDOT according to ASTM C 128.

2.2.2 Concrete Mixing and Curing

The concrete was mixed according ASTM C 192 "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory." The batch temperature was determined according to ASTM C 1064 "Standard Test Method for Temperature of Freshly Mixed Portland Cement Concrete." The slump was measured immediately after mixing in accordance with ASTM C 143 "Standard Test Method for Slump of Hydraulic Cement Concrete", except that 2 inch material was not removed from the slump sample.

The density was determined according to ASTM C 138, "Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric)". Total air content was determined according to ASTM C 173 "Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method".

For confined F-T testing, each aggregate source was evaluated based on three independent batches. In this study, the batches for each source were made on three different days. From each batch, two concrete cylinders (6 - by 12 inches) and three beams (6 - by 6 - by 15.5 inches) were made and cured according to ASTM C 192 "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory." Consolidation was by rodding. The large size beams were required for testing aggregate gradations with a maximum size of 2½ inches.

2.3 Freeze-Thaw Evaluation of Large Coarse Aggregate

2.3.1 Confined F-T Testing

The concrete beams were conditioned and subjected to freeze-thaw cycles as outlined in ASTM C 666 "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing" as well as MTM 114 and 115. At the age of 13 days, the concrete beams were removed from the 73° F curing water and immersed into a 40° F water bath for conditioning. After 24 hours, the concrete beams were removed from the chilled water and the initial lengths were determined. The concrete specimens are completely surrounded by air during the freezing phase of the cycle and by water during the thawing phase as outlined in Procedure B.

The nominal freezing-and-thawing cycle of Procedure B consists of alternately lowering the temperature from 40 to 0° F and raising it from 0 to 40° F in not less than 2 hours nor more than 5 hours. To conform to current MDOT practice, the nominal cycle length of 3 hours was selected.

The control length and the length change were determined using a length comparator as described in ASTM C 490 "Standard Practice for Use of Apparatus for the Determination of Length Change of Hardened Cement Paste, Mortar, and Concrete."

The beams were subjected to 300 freeze-thaw cycles. However if a beam cracked, it was removed from the F-T machine, and replaced with a dummy beam to maintain constant volume in the chamber throughout the testing period. The first length change reading was typically taken after 8 freeze-thaw cycles, and then at intervals not exceeding 36 cycles according to ASTM C 666. After freeze-thaw testing the beams were subjected to petrographic analysis in order to evaluate the extent and causes of cracking. See Section 2.5.

2.3.2 MDOT Dilation Specification Values for Coarse Aggregate Use in PCC

Current MDOT maximum dilation limit for coarse aggregate use in concrete is 0.067% per 100 F-T cycles. The maximum dilation is 0.040% per 100 F-T cycles for coarse aggregate used in pavement concrete with more than 5000 average daily traffic (ADT).

Pre-stressed concrete requires coarse aggregates which produce less than or equal to 0.010% dilation per 100 cycles (Table 902-2, MDOT Standard Specification, 1996) [10].

2.3.3 Unconfined F-T Testing of Large Coarse Aggregate

Unconfined testing of the coarse aggregate was also conducted, where the objective is to determine the percent mass loss during repeated freezing and thawing. MTM 124 was developed for evaluating large coarse aggregate sizes for railroad ballast. It is currently used as a screening method for aggregates submitted for freeze-thaw testing. The coarse aggregates were subjected to 300 freeze-thaw cycles in the same manner as outlined in Section 2.3.1. However, it was moisture conditioned by soaking for 24 hours prior to F-T testing.

The procedure for selecting the large coarse aggregate for unconfined testing was modified from the MTM procedure for this study. Representative coarse aggregate particles were selected for each sieve such that each petrographic subgroup was present. The number of particles for detailed petrographic evaluation was equal to the number of particles used for unconfined testing. Table 2.3.1 lists the sieve fractions and the quantities before testing.

Table 2.3.1 Sieve Size and Particle Number for Unconfined Testing.

Sieve Size (inch)	No. of Particles
2	15
1½	30
1	30
¾	30
½	30

The coarse aggregate was washed and oven dried. The weight of the material for each standard sieve was determined. In addition, for comparison, the actual fraction weights before testing are listed. Typically, the total source weights ranged from 20 to 25 lbs, which is slightly lower than the weights used in MTM 124 (33 lbs). However, selecting a given number of aggregate particles representing the source instead of a predetermined weight was considered more appropriate for this type of analysis.

The material was separated and bagged by size and was then submerged in cold water (40° F) for 24 hours prior to the freeze-thaw testing. The cloth bags were labeled with a water-freeze resistant label and placed in wire baskets in the freeze-thaw machine. These aggregates were subjected to 300 freeze-thaw cycles. The unbroken and broken (loss) particles from each bag were separated upon removing the aggregates from the freeze-thaw machine. The intact and broken (loss) particles were oven dried, sieved, and their weights were determined. The results were reported in percent mass loss per sieve size.

2.4 Compressive Strength Testing

The 28 day compressive strength of each batch of concrete was determined. Concrete cylinders were removed from the curing water and capped according to ASTM C 617 "Standard Practice for Capping Cylindrical Concrete Specimens." The compressive strength was determined according to ASTM C 39 "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens."

2.5 Petrography- Characterization of Concrete Beams and Aggregates

Petrographic analyses were completed on the concrete beams from the freeze-thaw tests and on the coarse aggregates before and after the unconfined freeze-thaw tests.

2.5.1 Characterization of Concrete Beams

The concrete beams were analyzed macroscopically for types (pop-outs, spalling, and cracking) and extent (number of cracks and their spacing) of freeze-thaw deterioration. At least two selected concrete beams representing each aggregate source were subsequently cut in slices across observed cracks to define which aggregates and/or other factors were responsible for the internal freeze-thaw damage.

2.5.2 Characterization of Coarse Aggregates

The aggregates for the unconfined test were characterized following the general outline of the checklist in Table 2.6. The characterization in the checklist was chosen based on the recommendations in ASTM C 295 "Practice for Petrographic Examination of Aggregates for Concrete." A 0.1 molar HCl solution was used for carbonate reaction analysis. A magnifying lens (10X), a stereomicroscope, and a steel knife were used to evaluate the aggregate hardness.

Petrographic analysis of the aggregates was completed on approximately 135 particles from each aggregate source. These were picked from washed, sieved, and oven-dried material. The particles were selected and described using Table 2.5.1.

The petrographic evaluation focused on identifying the rock types present as aggregates (i.e., shale, dolomite, gabbro), and determination of calcite in carbonate rocks. Deleterious constituents were determined from visual inspection. Presence of calcite was determined by the hydrochloric acid test (0.1M). The degree of acid reaction determines whether the carbonate rock is predominantly a dolomite, limey dolomite, or limestone. The presence of macro-fractures was determined by visual inspection of the sieved aggregates aided by the 10X magnifier lens.

Micro-porosity (here defined as the porosity not visible to the naked eye) of the aggregates was determined by the stickiness felt on one's tongue. In this test, the stickiness increases with increasing micro-porosity as function of the amount of water the aggregate can absorb from the tongue. This method enabled the classification of aggregate in terms of relative high, medium, or low micro-porosity.

Table 2.5.1 Standard Petrographic Evaluation of Large Size Coarse Aggregate

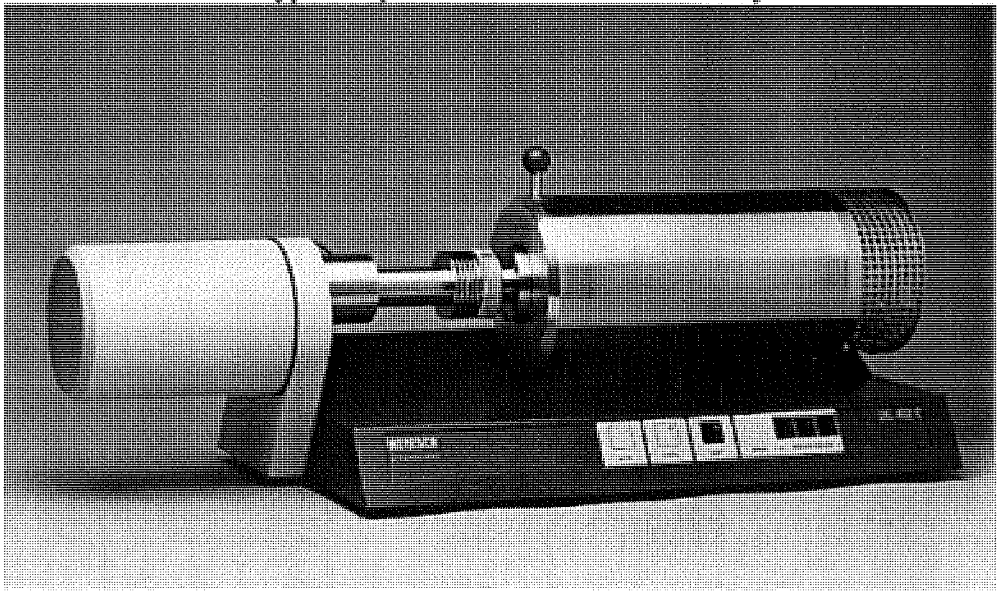
SOURCE:

Retained on the_____inch sieve

Rock type (s) incl. definition of Gravel Crushed rock	
Mineral composition	
Texture/structure/fracture	
Coatings	
Typical shape(s)	
Weathering condition 1) fresh 2) moderately weathered 3) severely weathered	
Relative Micro-Porosity (high, medium, low)	

2.6 Unconfined Dilation During Freezing of Coarse Aggregate

A special testing apparatus was utilized to determine the unconfined dilation during freezing of individual coarse aggregate (saturated) samples (about 1.7 inch long, 0.4 inch wide, and 0.2 inch thick). The test set-up includes a low-temperature dilatometer and heating-cooling control unit. Figure 2.6.1 shows the low-temperature dilatometer and sample holders. The tube-type sample holder is used in this study.



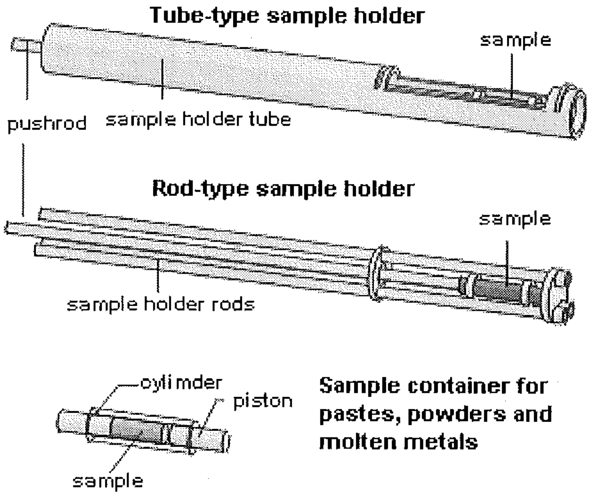


Figure 2.6.1 Low Temperature Chamber and Sample Holder (Tube-Type used in This Study.)

This special set-up was required to obtain continuous measurements of dilation and temperature in order to capture the dilation during freezing of the pore water. The temperature range used in this study was from room temperature to approximately -10 °F. The heating and cooling rate was 0.9° F/min. The dilation was measured with an LVDT sensor with a range of ±0.0098 inches. The LVDT sensor was zeroed at room temperature.

CHAPTER 3 - PETROGRAPHY OF COARSE AGGREGATE SOURCES PRIOR TO F-T TESTING

This chapter presents the results of the aggregate analysis for each of the sources used in this study. A summary of the results and comparison between the sources is given at the end of the chapter.

3.1 DOLOMITE 1

Dolomite 1 is located in the Engadine Dolomite Formation, Niagaran Group, and is of Middle Silurian age. The Engadine Formation is divided into two layers, the Rockview Dolostone, and the Rapson Creek Dolostone. The coloration of these aggregates is usually white to buff, mottled white to gray, or gray. The particles are composed of fine-grained to microcrystalline, subhedral to anhedral, slightly porous dolomite with a Mohs scratch hardness of 3.5 to 4 (R. Muethel, MDOT) [11].

3.1.1 Aggregate Subtypes

Four aggregate subtypes were observed in the representative sample from the Dolomite 1 quarry (Table 3.1.1, Figure 3.1.1). However, gray dolomite (72.6%) and a rusty beige dolomite (25.9%) (Figure 3.1.1a and c) strongly dominated the source.

Both of these aggregate subtypes were occasionally bedded and contained rust colored (Fe-oxyhydroxide) coatings. The gray dolomite occasionally contained residual coral. Some of the gray dolomite particles contain rust regions showing that the dolomite is an oxidized version of the gray dolomite (Figure 3.1.1b). This caused the red colored coating on the rusty beige aggregates. Single particles of a white porous dolomite (Figure 3.1.1d) and a white meso-crystalline dolomite were also observed in the ¾ and 1 inch fraction, respectively.

In total, 63.0% of the aggregates contained cracks (Table 3.1.1), which were most abundant in gray dolomite particles.

Table 3.1.1 Petrographic Observations of Aggregate Particles from the Dolomite 1 Source

Crushed Stone (Angular)	**Sieve Size (inch)**						
Subtype	**½**	**¾**	**1**	**1½**	**2**	**Total**	**%**
gray dolomite	26	19	21	22	10	98	72.6
rusty beige dolomite*	4	10	8	8	5	35	25.9
white porous dolomite	0	1	0	0	0	1	0.7
white meso-crystalline dolomite	0	0	1	0	0	1	0.7
Total	30	30	30	30	15	135	100.0
number of aggregates with cracks	16	11	24	23	11	85	63.0
number of aggregates with coatings*	4	10	8	8	5	35	25.9

*red-colored coating on almost all the rusty beige dolomite aggregates

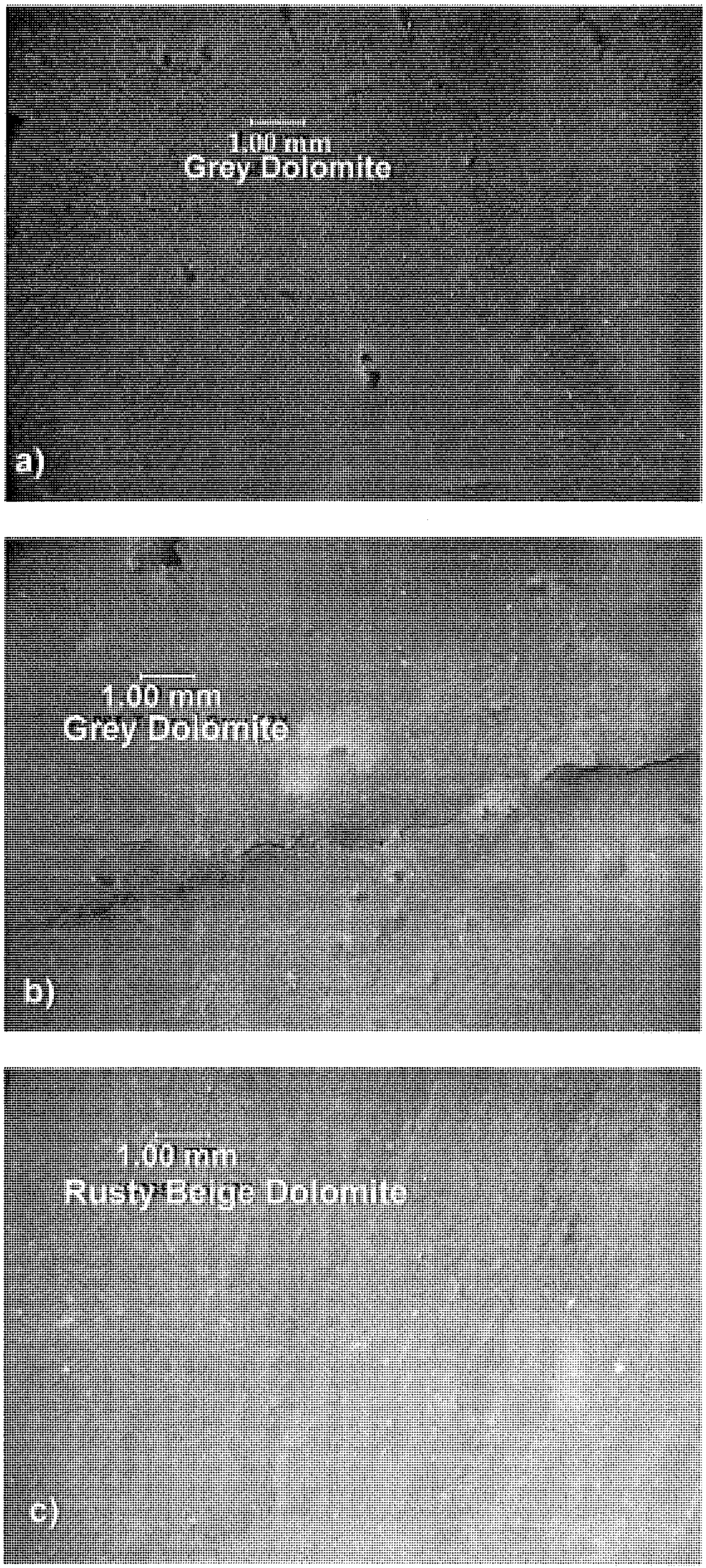


Figure 3.1.1 Source variability in Dolomite 1. Magnification 13X. a) and b) Grey Dolomite, and c) Rusty Beige Dolomite.

3.1.2 Relative Micro-Porosity

The number of highly porous aggregates from the Dolomite 1 source appears to be low (Table 3.1.2).

Table 3.1.2 Evaluation of Relative Micro-Porosity of Aggregates from the Dolomite 1 Source

Micro-Porosity	Sieve Size (inch)					Total	%
	½	¾	1	1½	2		
Low	26	25	29	27	13	120	88.9
Medium	4	4	1	2	2	13	9.6
High	0	1	0	1	0	2	1.5
Total	30	30	30	30	15	135	100.0

3.2 DOLOMITE 2

Dolomite 2 is located in the Raisin River Dolomite Formation overlying the Put-in-Bay Dolomite Formation. Both of these formations belong to the Bass Island Group of late Silurian age. Aggregates from this quarry have a buff, gray, and mottled gray to buff color and typically are composed of fine-grained to microcrystalline, dense to porous dolomite with a Mohs scratch hardness of 3.5 to 4. Some particles have high insoluble residue content (R. Muethel, MDOT).

3.2.1 Aggregate Subtypes

Eight different aggregate subtypes were observed in the representative sample from the Dolomite 2 source (Table 3.2.1). The majority of the aggregates consisted of various shades of brown dolomite (47%) and an inhomogeneous dolomite (40.0%). Mottled dolomite (2.9%) also occurred among these aggregates. Coatings of stylolitic shale and shale bedding surfaces were observed in 20.7% of the particles. In this study, the term coatings refers to any exposed stylolitic shale, calcite or fossiliferous material on an aggregate surface. Examples of these aggregate subtypes are shown in Figure 3.2.1a-f.

Table 3.2.1 Petrographic Observations of Aggregate Particles from the Dolomite 2 Source

Crushed Stone	**Sieve Size (inch)**						
Subtype	**½**	**¾**	**1**	**1 ½**	**2**	**Total**	**%**
shale	1	0	0	4	5	10	7.1
shaly dolomite	0	0	2	0	0	2	1.4
dark brown dolomite	2	5	7	5	0	19	13.6
reddish brown dolomite	0	2	0	0	0	2	1.4
light brown dolomite	7	11	13	11	3	45	32.1
mottled dolomite	0	3	1	0	0	4	2.9
inhomogeneous dolomite	20	11	7	11	7	56	40.0
porous white dolomite	0	0	0	1	1	2	1.4
Total	30	32	30	32	16	140	100.0
number of aggregates with cracks	7	11	12	15	16	61	43.6
number of aggregates with coatings of stylolitic shale and shale bedding surfaces	0	4	7	11	6	28	20.7

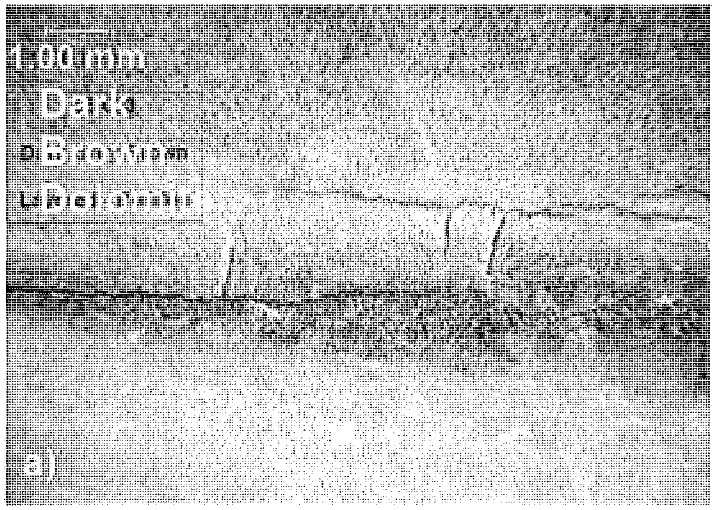
Critical for this source is the presence of more than 8% shale and shaly dolomite. The performance of the shale component was expected to be critical in water-saturated freeze-thaw testing (Figure 3.2.1d-e). Other characteristics that may be of importance are the occasional white precipitate coating on aggregates from the ½ sieve size and the presence of stylolite and shale coatings (Figure 3.2.1d-e) on approximately 16% of the particles. Cracks were observed in 43.6% of the aggregates.

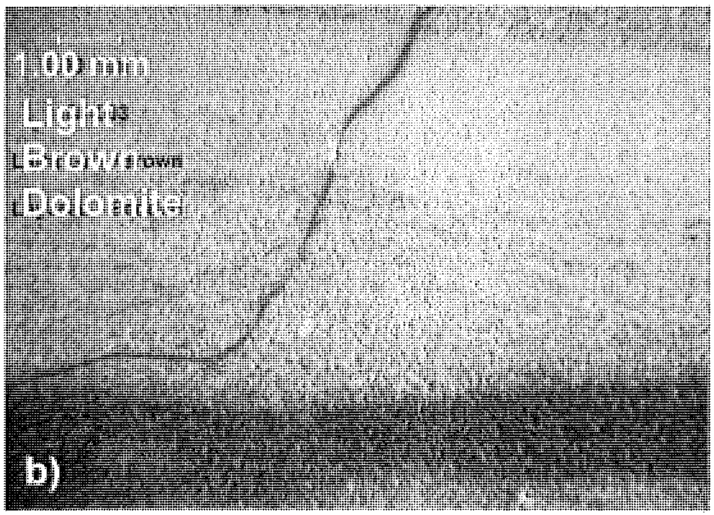
3.2.2 Relative Micro-Porosity

The micro-porosity test method as described in paragraph 2.5.2 indicated that approximately 26% of the aggregates have medium micro-porosity and 6% have high micro-porosity (Table 3.2.2). There was a negligible difference in the microporosity between the various aggregate size fractions.

Table 3.2.2 Evaluation of Relative Micro-Porosity of Aggregates from Dolomite 2 Source

Micro-Porosity	Sieve Size (inch)					Total	%
	½	¾	1	1½	2		
Low	21	20	20	22	12	95	67.9
Medium	9	8	7	9	3	36	25.7
High	0	4	3	1	1	9	6.4
Total	30	32	30	32	16	140	100.0





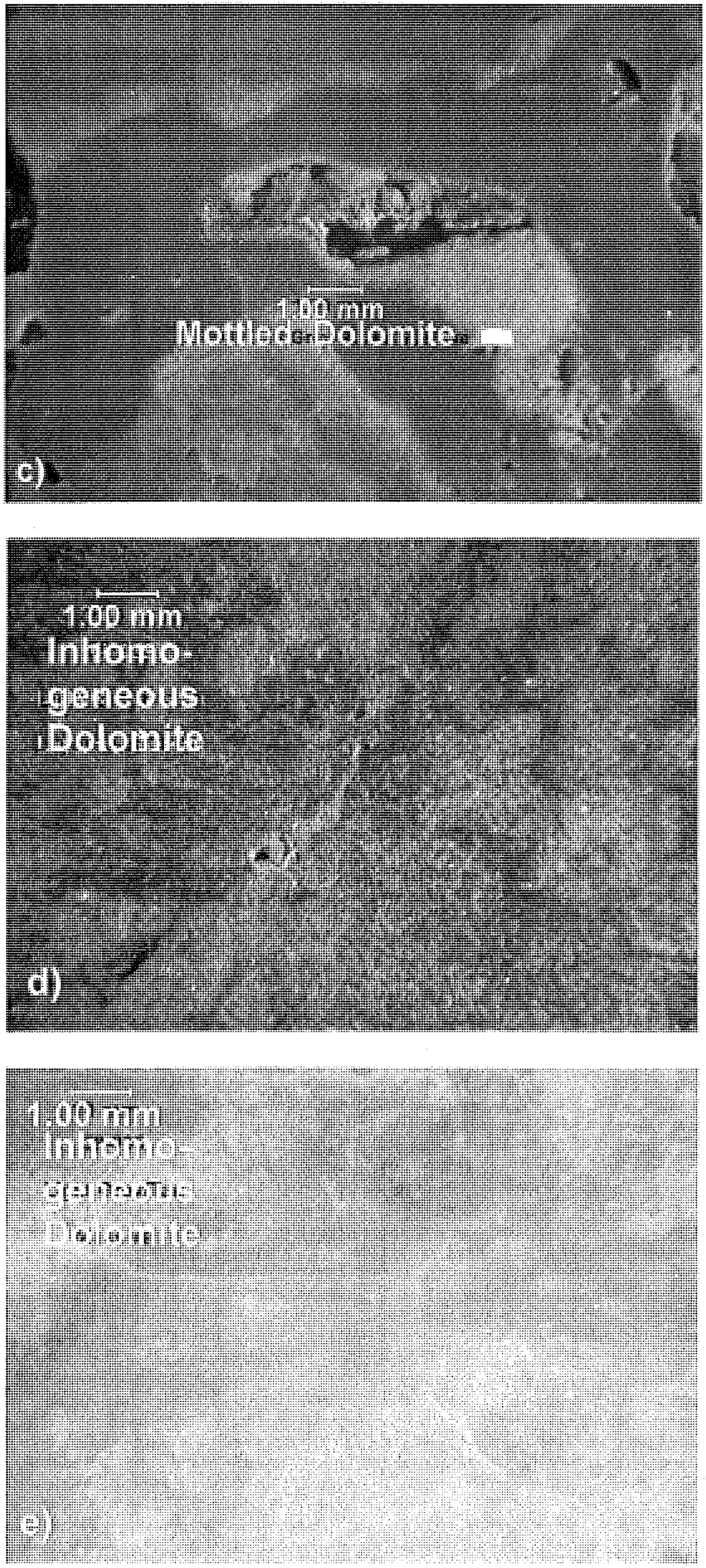


Figure 3.2.1 Source variability in Dolomite 2. Magnification 13X. a) Dark Brown Dolomite, b) Light Brown Dolomite, c) Mottled Dolomite, d) Inhomogeneous Dolomite, and e) Inhomogeneous Dolomite.

3.3 DOLOMITE 3

Dolomite 3 is located in the base of the Bois Blanc Formation, Detroit River Group of Devonian age and the Raisin River Formation, Bass Island Group of late Silurian age. Concrete aggregates from this quarry typically have a light gray-brown to gray color. The aggregates are usually fine-grained to microcrystalline and consist of limey dolomite with a Mohs scratch hardness of 3.5 to 4 (R. Muethel, MDOT).

3.3.1 Aggregate Subtypes

The representative sample contained eight different aggregate subtypes dominated by medium to dark-brown dolomite (59.5%; Table 3.3.1). The less abundant types included white, gray, oolithic inhomogeneous, and mottled dolomite, as well as a gray marl-like aggregate with stylolites. Some of the aggregates were layered. Additionally, the brown aggregates occasionally contained thin layers (0.04 inches to 0.08 inches thick) of inter bedded shale. Figure 3.3.1 shows examples of the aggregate subtypes observed in the sample.

Table 3.3.1 Petrographic Observations of Aggregate Particles from the Dolomite 3 Source

Crushed stone	Sieve Size (inch)						
Subtype	½	¾	1	1½	2	Total	%
oolitic dolomite	1	1	0	0	0	2	1.5
white dolomite$	6	0	0	0	0	6	4.4
gray dolomite$	0	3	1	15	1	20	14.7
medium brown dolomite$	16	17	16	0	9	58	42.6
dark brown dolomite$	7	5	4	7	0	23	16.9
inhomogeneous dolomite	0	2	0	0	0	2	1.5
mottled dolomite	0	2	8	8	5	23	16.9
gray "marl" with stylolites	0	1	1	0	0	2	1.5
Total	30	31	30	30	15	136	100.0
number of aggregates with cracks	6	6	7	10	5	34	25.0
number of aggregates with coatings*	6	5	5	11	6	33	24.3

$ some aggregates are layered; * thin shale layers or stylolite coatings

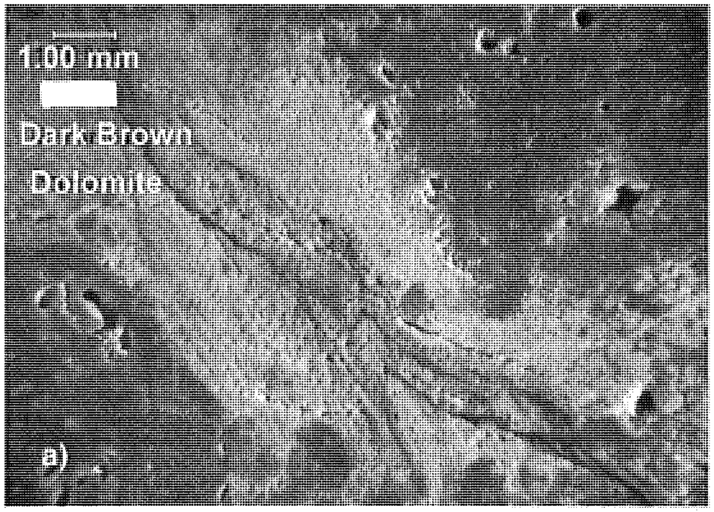
The cracking that was observed was most frequently in the brown and the inhomogeneous dolomite. In total, 25% of the aggregates contained visible micro-cracks. A similar percentage of the aggregates contained coatings of shale or fine stylolitic shale.

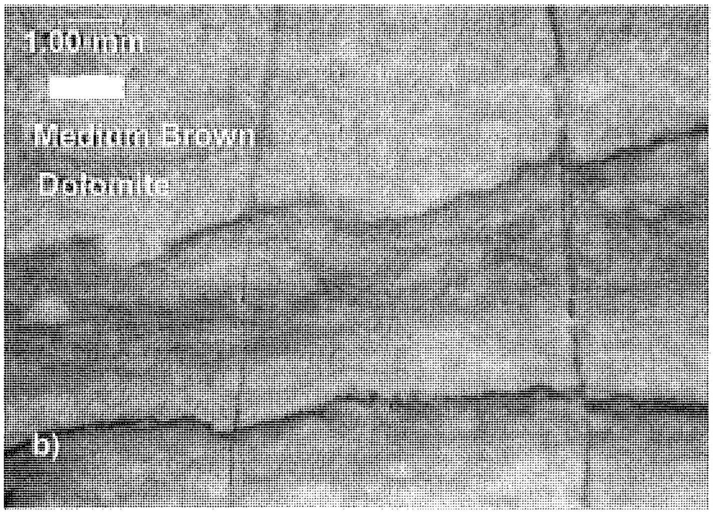
3.3.2 Micro-Porosity

Analysis of the aggregates from the Dolomite 3 source showed that a relatively high number of aggregate particles (51.5%) had elevated micro-porosity. High micro-porosity was found in 19.9% of the aggregates and 31.6% had a medium level of micro-porosity.

Table 3.3.2 Evaluation of Micro-Porosity of Aggregates from the Dolomite 3 Source

Micro-Porosity	**Sieve Size (inch)**					**Total**	**%**
	½	**¾**	**1**	**1½**	**2**		
Low	13	11	11	20	11	66	48.5
Medium	12	14	11	6	0	43	31.6
High	5	6	8	4	4	27	19.9
Total	30	31	30	30	15	136	100.0





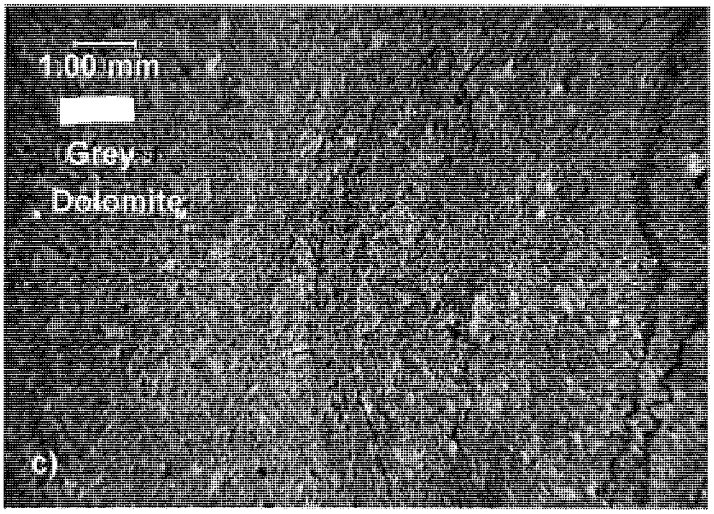


Figure 3.3.1 Source variability in Dolomite 3. Magnification 13X. a) Dark Brown Dolomite, b) Medium Brown Dolomite, and c) Grey Dolomite.

3.4 DOLOMITE 4

Dolomite 4 is located in the Put-in-Bay Dolomite Formation, lower Bass Island Group, of late Silurian age. Typically, aggregates from this quarry are gray, and composed of very fine-grained, dense to porous, slightly limey dolomite. The Mohs scratch hardness is 3 to 3.5. Some particles have high micro-porosity (R. Muethel, MDOT).

3.4.1 Aggregate Subtypes

Five different subtypes of aggregates were observed in the representative sample from the Dolomite 4 quarry (Table 3.4.1). Overall, each of the aggregate subtypes occurred with similar abundance. Beige-brown and brown dolomite particles had the highest percentage. A large fraction of the aggregates were bedded and/or contained stylolitic shale (64.4%). Examples of the aggregates are shown in Figure 3.4.1. Cracks were abundant relative to other aggregates investigated in this study. They were observed in 49.6% of the particles. Some of the cracks were observed in bedding planes of the layered particles. Coatings with shale or stylolite were observed in 21.5% of the particles.

Table 3.4.1 Petrographic Observations of Aggregate Particles from Dolomite 4

Crushed stone	**Sieve Size (inch)**						
Subtype	**½**	**¾**	**1**	**1½**	**2**	**Total**	**%**
gray layered dolomite[$]	4	5	3	8	3	23	17.0
beige-brown layered dolomite[$]	5	8	5	6	5	29	21.5
beige-brown dolomite[#]	12	7	8	4	4	35	25.9
brown dolomite[#]	5	6	7	4	1	23	17.0
inhomogeneous brown dolomite	4	4	7	8	2	25	18.5
Total	30	30	30	30	15	135	100.0
number of aggregates with cracks	7	18	16	17	9	67	49.6
number of aggregates with coatings[*]	2	4	9	7	7	29	21.5

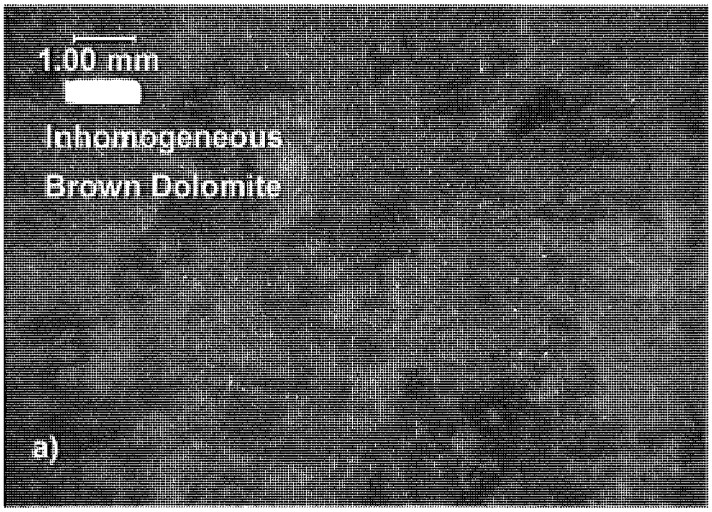
[$] often with thin shaly/stylolite layers
[#] occasionally with visible (i.e. macroscopic) pores
[*] shale/stylolite

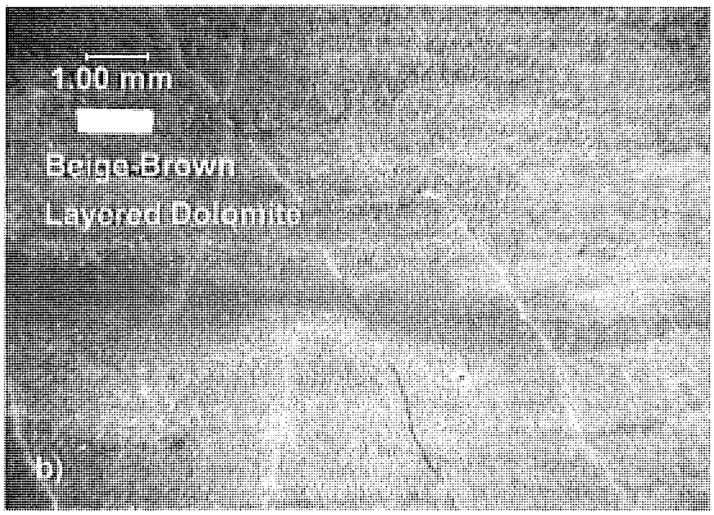
3.4.2 Relative Micro-Porosity

Evaluation of the micro-porosity of the aggregates showed that approximately 70% of the sample was elevated (Table 3.4.2). A medium level of micro-porosity was found in 43.7% of the aggregates whereas 25.9% had a very high degree of micro-porosity. Correlation with aggregate subtypes showed that the brown dolomite particles generally were the least porous aggregate subtype in the source. However, small and more light-colored areas in the brown particles had elevated micro-porosity. The highest micro-porosity was usually found in the gray layered dolomite and in the inhomogeneous dolomite particles.

Table 3.4.2 Evaluation of Relative Micro-Porosity of Aggregates from Dolomite 4

Micro-Porosity	**Sieve Size (inch)**					**Total**	**%**
	½	**¾**	**1**	**1½**	**2**		
Low	6	10	10	10	5	41	30.4
Medium	17	14	9	13	6	59	43.7
High	7	6	11	7	4	35	25.9
Total	30	30	30	30	15	135	100.0





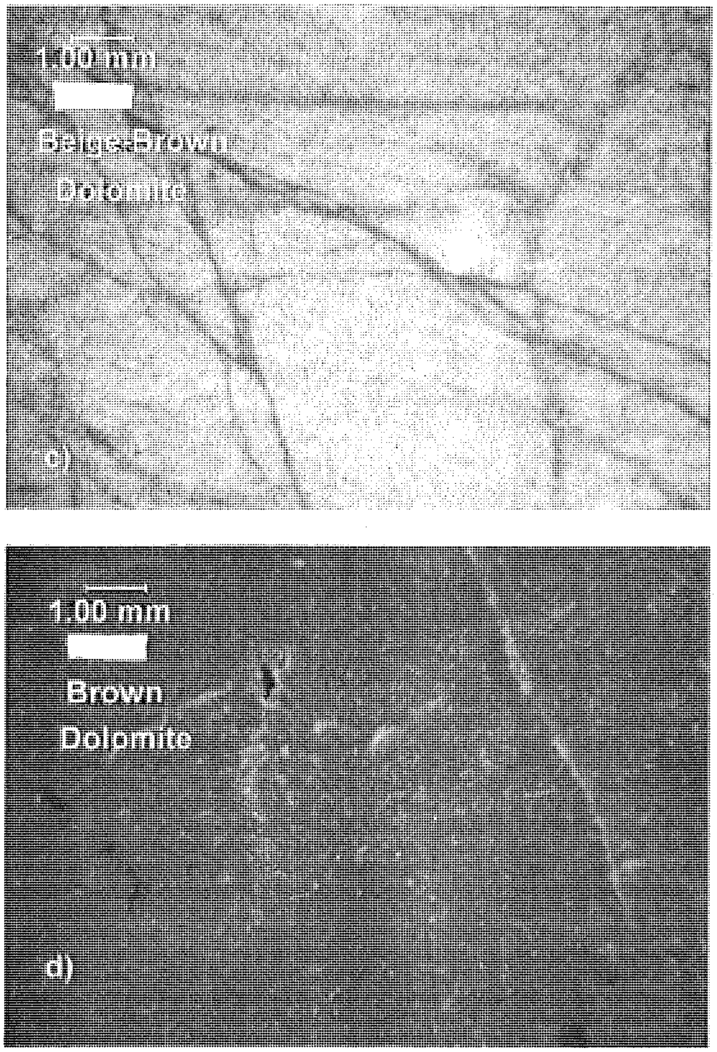


Figure 3.4.1 Source variability in Dolomite 4. Magnification 13X. a) Inhomogeneous Brown Dolomite, b) Beige-Brown Layered Dolomite, c) Beige-Brown Dolomite, and d) Brown Dolomite

3.5 DOLOMITE 5

Dolomite 5 is situated in Ohio approximately five miles southwest of the Dolomite 2 Quarry in Michigan. By correlation, it is located in bedrock of late Silurian age. Aggregates used in concrete from this quarry normally have a gray buff color with darker gray zones. The particles are fine-grained to micro-crystalline, dense to slightly porous dolomite with a Mohs scratch hardness of 3.5 to 4 (R. Muethel, MDOT).

3.5.1 Aggregate Subtypes

Six different aggregate subtypes were observed in the Dolomite 5 source (Table 3.5.1 and Figure 3.7.1). Mottled dolomite (73.1%) and a beige-red-brown dolomite (16.8%) were the most dominant aggregate subtypes (Figure 3.7.1a-b). Minor amounts of gray (5.8%) and white dolomite (2.9%), coral aggregates (0.7%), and dolomite with pelite (0.7%) was also present. Cracks were present in 35% of the aggregate particles. Stylolitic or shaley material was exposed on 7.4% of the particles.

3.5.2 Relative Micro-Porosity

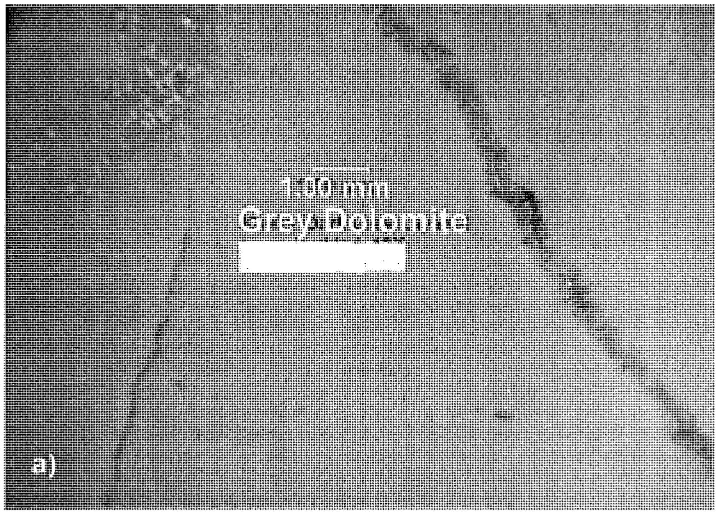
The micro-porosity results yielded 75.9% of the aggregates having low relative micro-porosity. Medium and high micro-porosities were found in 19.0% and 5.1% of the aggregates, respectively.

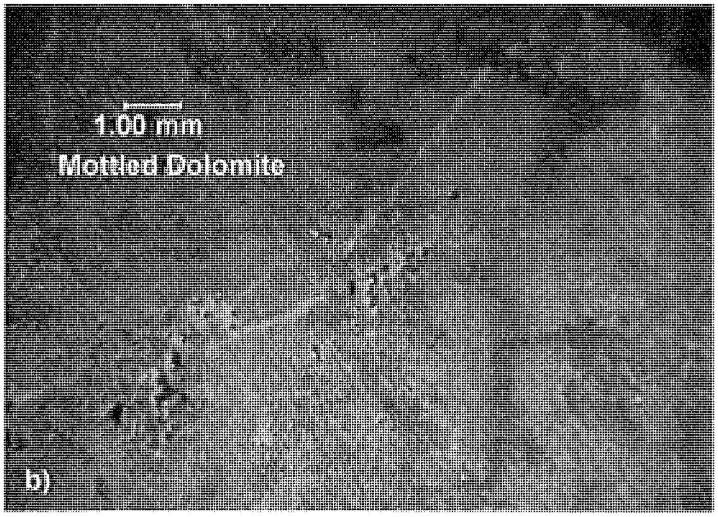
Table 3.5.1 Petrographic Observations of Aggregate Particles from the Dolomite 5 Source

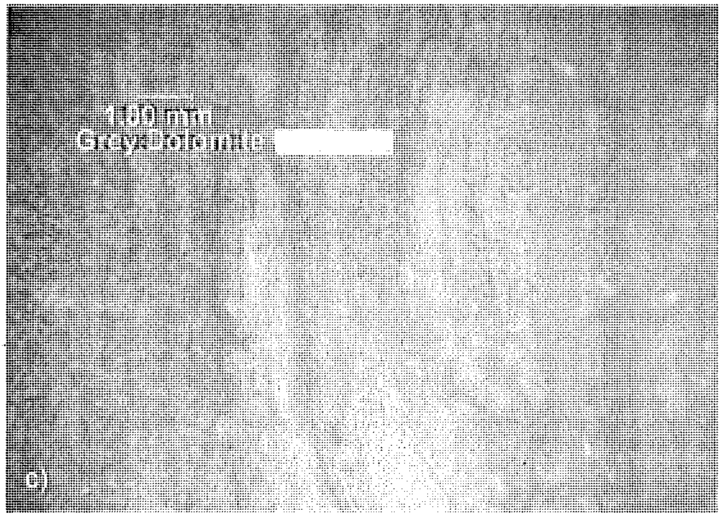
Crushed Stone	**Sieve Size (inch)**						
Subtype	**½**	**¾**	**1**	**1½**	**2**	**Total**	**%**
mottled dolomite	19	23	25	22	11	100	73.1
gray dolomite	5	0	0	3	0	8	5.8
beige-red brown dolomite	8	5	2	5	3	23	16.8
white dolomite	0	2	2	0	0	4	2.9
dolomite with pelite	0	0	1	0	0	1	0.7
white coral	0	0	0	0	1	1	0.7
Total	32	30	30	30	15	137	100.0
number of aggregates with cracks	10	9	8	9	12	48	35.0
number of aggregates with exposed stylolite/shale	2	0	0	4	4	10	7.4

Table 3.5.2 Evaluation of Relative Micro-Porosity of Aggregates from the Dolomite 5 Source.

Micro-Porosity	**Sieve Size (inch)**					**Total**	**%**
	½	**¾**	**1**	**1½**	**2**		
low	31	18	22	21	12	104	75.9
medium	1	11	4	7	3	26	19.0
high	0	1	4	2	0	7	5.1
Total	32	30	30	30	15	137	100.0



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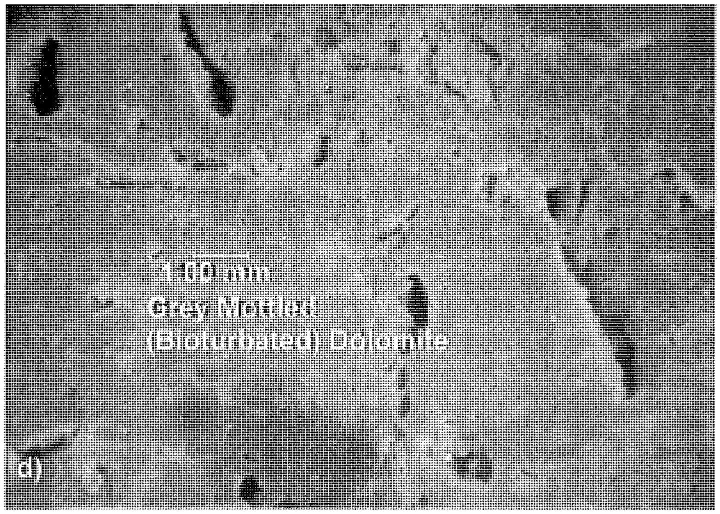
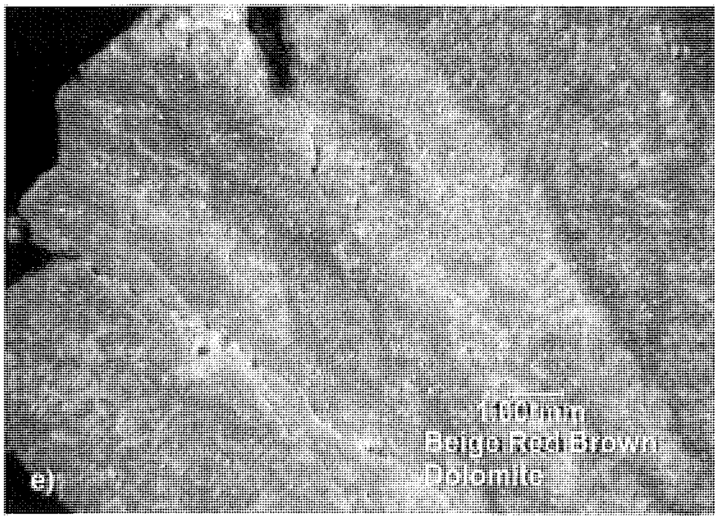
Grey Dolomite
c)


1.00 mm
Grey Mottled
(Bioturbated) Dolomite
d)


1.00 mm
Beige Red-Brown
Dolomite
e)

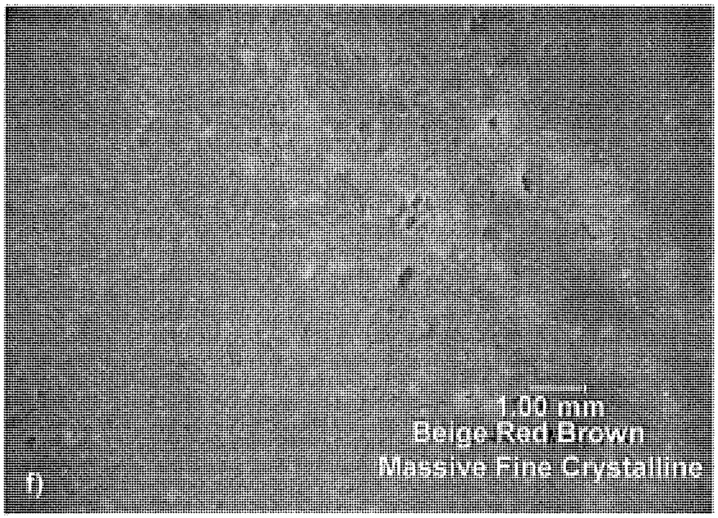


Figure 3.5.1 Source variability in Dolomite 5. Magnification 13X. a) Grey Dolomite, b) Mottled Dolomite, c) Grey Dolomite, d) Mottled Dolomite, e) Beige Red Brown Dolomite, and f) Beige Red Brown, Massive Fine Crystalline Dolomite.

3.6 DOLOMITE 6

Dolomite 6 is located in the Amabel Formation of late Silurian age. Aggregates from this quarry have white to light gray color. The particles are composed of fine-grained, slightly porous dolomite with a Mohs scratch hardness of 3.5 to 4 (R. Muethel, MDOT).

3.6.1 Aggregate Subtypes

Two different aggregate subtypes were observed in the representative sample of Dolomite 6 (Table 3.6.1). The dominant aggregate subtype was gray dolomite (75.9%). The remaining aggregate subtype showed lighter colors ranging from light-gray to white and was occasionally partially rust-colored. Cracks were observed in 32.8% of the particles. Stylolitic shale or a greenish fracture filling was exposed on 15.3% of the particles. Examples of the aggregate subtypes are shown in Figure 3.6.1.

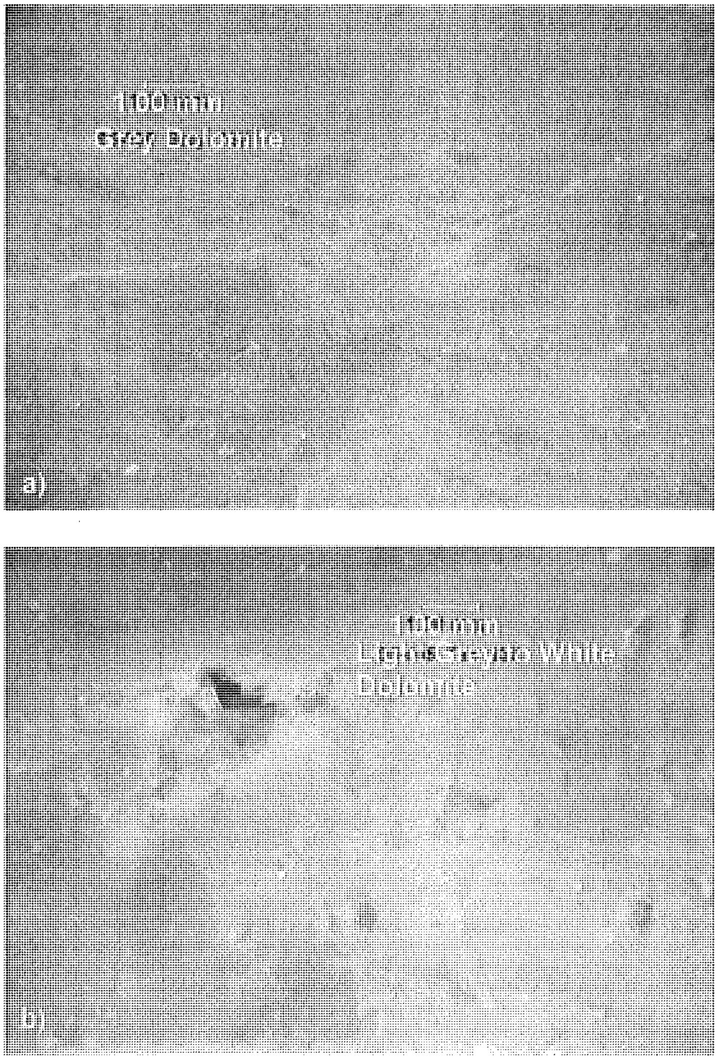


Figure 3.6.1 Source variability in Dolomite 6. Magnification 13X. a) Grey Dolomite, and b) Light Grey to White Dolomite

Table 3.6.1 Petrographic Observations of Aggregate Particles from Dolomite 6

Crushed Stone	**Sieve Size (inch)**						
Subtype	½	¾	**1**	**1½**	**2**	**Total**	**%**
gray dolomite	25	25	25	22	7	104	75.9
light-gray to white dolomite	7	5	5	8	8	33	24.1
Total	32	30	30	30	15	137	100.0
number of aggregates with cracks	12	3	5	13	12	45	32.8
number of aggregates with exposed stylolitic shale or greenish fracture fillings	0	3	7	5	6	21	15.3

3.6.2 Micro-Porosity

Based on the petrographic analysis, the aggregates had low micro-porosity. Medium micro-porosity was only found in 1.5% of the particles (Table 3.6.2).

Table 3.6.2 Evaluation of Relative Micro-Porosity of Aggregates from Manitoulin Dolomite

Micro-Porosity	**Sieve Size (inch)**					**Total**	**%**
	½	¾	**1**	**1½**	**2**		
low	31	29	30	30	15	135	98.5
medium	1	1	0	0	0	2	1.5
high	0	0	0	0	0	0	0.0
Total	32	30	30	30	15	137	100.0

3.7 LIMESTONE 1

Limestone 1 is located in the Dundee Formation, Onondaga Group, of Devonian age. The aggregate from this quarry has buff to brown color. The particles are composed of medium to fine-grained and slightly porous limestone. The Mohs scratch hardness is 3 to 3.5 (R. Muethel, MDOT).

3.7.1 Aggregate Subtypes

Four different aggregate subtypes were observed in the sample (Table 3.7.1). Only two subtypes are of significance; 1) the beige-brown and 2) dark-brown limestone. These occur in approximately equal amounts. The other two aggregate subtypes were single pieces of bedded brown dolomite and coral found on the 0.5 inch sieve. Cracks were observed in 35.6% of the aggregate particles. Stylolitic shale, calcite and fossiliferous material was exposed on 23.7% of the aggregates. Examples of the aggregate subtypes are shown in Figure 3.7.1.

Table 3.7.1 Petrographic Observations of Aggregate Particles from Limestone 1

Crushed Stone Subtype	Sieve Size (inch) ½	¾	1	1½	2	Total	%
beige-brown limestone	13	11	22	16	8	70	51.9
dark brown limestone	15	19	8	14	7	63	46.7
bedded brown dolomite	1	0	0	0	0	1	0.7
coral	1	0	0	0	0	1	0.7
Total	30	30	30	30	15	135	100.0
number of aggregates with cracks	4	12	8	14	10	48	35.6
number of aggregates with exposed stylolitic shale, calcite or fossiliferous material	6	5	2	11	8	32	23.7

3.7.2 Relative Micro-Porosity

Of the aggregate sample evaluated, 32.6% had medium micro-porosity and 5.9% had high micro-porosity (Table 3.7.2). The elevated micro-porosities were generally found in the beige-brown aggregate subtype.

Table 3.7.2 Evaluation of Relative Micro-Porosity of Aggregates from Limestone 1

Micro-Porosity	Sieve Size (inch) ½	¾	1	1½	2	Total	%
low	22	17	12	22	10	83	61.5
medium	6	12	15	7	4	44	32.6
high	2	1	3	1	1	8	5.9
Total	30	30	30	30	15	135	100.0

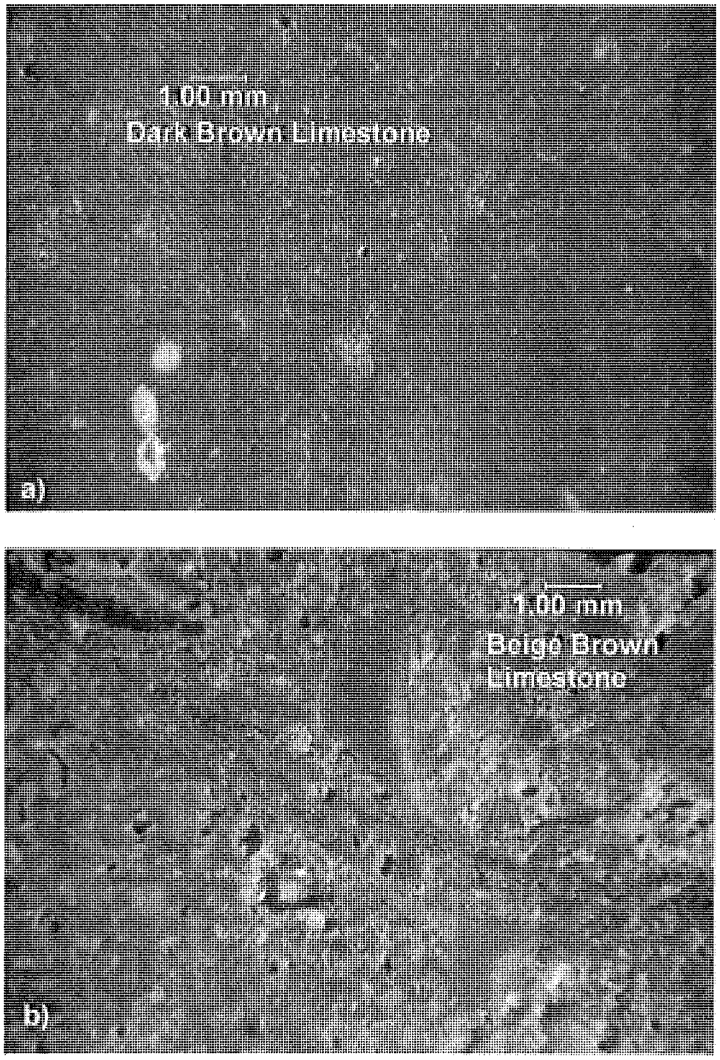


Figure 3.7.1 Source variability in Limestone 1. Magnification 13X. a) Dark Brown Limestone, and b) Beige Brown Limestone

3.8 LIMESTONE 2

Limestone 2 is located in the Dundee Formation, Onandaga Group, of Devonian age. The aggregates from this quarry that are used in concrete are buff to brown and dark gray. The particles are composed of medium to fine-grained and slightly porous dolomitic limestone. The Mohs scratch hardness is 3 to 3.5 (R. Muethel, MDOT).

3.8.1 Aggregate Subtypes

Two aggregate subtypes were identified in the representative sample from Presque Isle (Table 3.8.1 and Figure 3.8.1). Almost 74% of the aggregate sample consisted of a brown dolomitic limestone whereas 26.1% consisted of a light brown dolomitic limestone. The particles occasionally contained fossil coral (Figure 3.8.1b). The number of particles containing cracks was 24.3%, and 33.9% of the particles were partially coated with stylolitic shale.

Table 3.8.1 Petrographic Observations of Aggregate Particles from Limestone 2

Crushed Stone	**Sieve Size (inch)**						
Subtype	**½**	**¾**	**1**	**1½**	**2**	**Total**	**%**
brown dolomitic limestone	22	22	6	25	10	85	73.9
light brown dolomitic limestone	8	8	4	5	5	30	26.1
Total	30	30	10	30	15	115	100.0
number of aggregates with cracks	6	5	4	8	5	28	24.3
number of aggregates with coatings*	9	8	4	13	5	39	33.9

*stylolite coatings

3.8.2 Relative Micro-Porosity

Limestone 2 aggregates typically had a low micro-porosity, with 84.3% having a very low micro-porosity (Table 3.8.2). The remaining 15.7% were found to have a medium micro-porosity.

Table 3.8.2 Evaluation of Relative Micro-Porosity of Aggregates from Limestone 2

Micro-Porosity	**Sieve Size (inch)**					**Total**	**%**
	½	**¾**	**1**	**1½**	**2**		
low	28	21	7	27	14	97	84.3
medium	2	9	3	3	1	18	15.7
high	0	0	0	0	0	0	0.0
Total	30	30	10	30	15	115	100.0

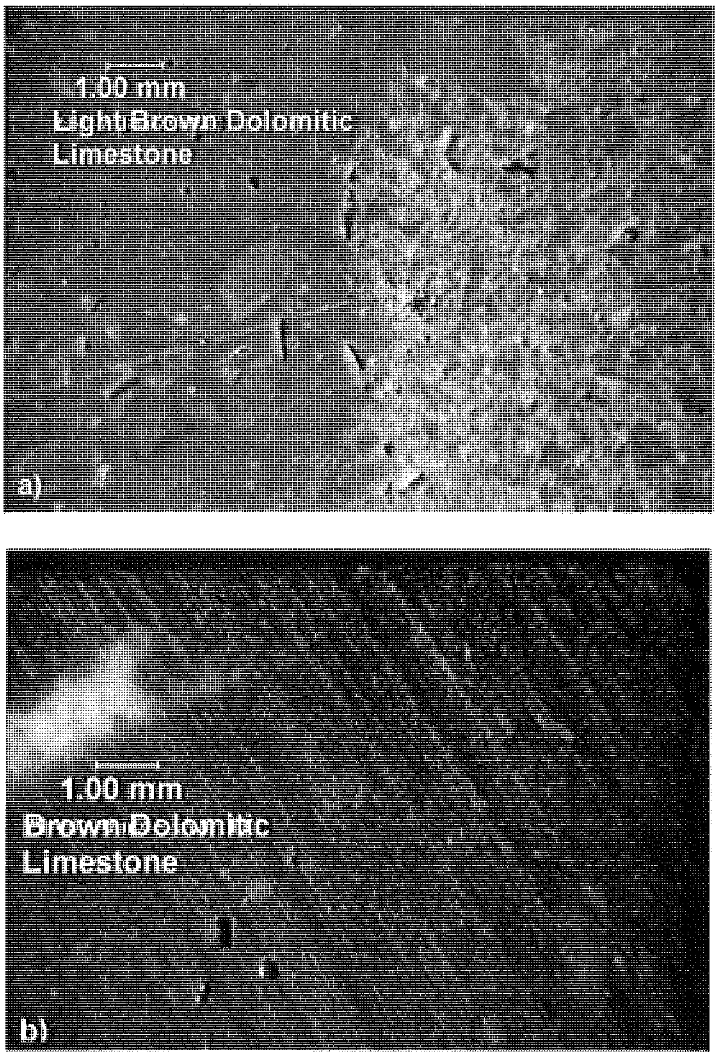


Figure 3.8.1 Source variability in Limestone 2. Magnification 13X. a) Light Brown Dolomitic Limestone, and b) Brown Dolomitic Limestone

3.9 LIMESTONE 3

Limestone 3 is located in the Fiborn Limestone Member of the Hendriks Dolomite Formation, Burnt Bluff Group of Middle Silurian age. Aggregates used in concrete from this quarry have a buff to grayish-buff color. The particles are composed of microcrystalline and slightly porous limestone with a Mohs scratch hardness of 3 (R. Muethel, MDOT).

3.9.1 Aggregate Subtypes

Two aggregate subtypes were identified in the representative sample from 75-05. A beige-brown limestone (94.8%) predominated over a lighter beige-brown subtype (5.2%) (Table 3.9.1 and Figure 3.9.1). The aggregates were rarely layered, but occasionally the beige-brown limestone had a fine fenestral texture. Additionally, residual coral was observed and a single aggregate consisted mostly of coral. Both aggregate subtypes sometimes contained small voids and cracks (up to 0.04 inch) filled with drusy carbonate. Aggregates with cracks were most abundant in the material retained on 1 inch (50%) and 1½ inch (47%) sieves, and cracks were found in 33% of the aggregates in the complete sample. Notably, coatings were not observed on aggregates from this source.

Table 3.9.1 Petrographic Observations of Aggregate Particles from the Limestone 3 Source

Crushed Stone	**Sieve Size (inch)**						
Subtype	**½**	**¾**	**1**	**1½**	**2**	**Total**	**%**
beige brown limestone	28	30	27	30	13	128	94.8
light beige brown limestone	2	0	3	0	2	7	5.2
Total	30	30	30	30	15	135	100.0
number of aggregates with cracks	2	9	15	14	5	45	33.3
number of aggregates with coatings	0	0	0	0	0	0	0.0

3.9.2 Relative Micro-Porosity

The relative micro-porosity of aggregates from the Limestone 3 source was generally very low (Table 3.9.2). Only 3.7% of the sample were found to have a medium micro-porosity, and none had high micro-porosity.

Table 3.9.2 Evaluation of Relative Micro-Porosity of Aggregates from Limestone 3

Micro-Porosity	**Sieve Size (inch)**					**Total**	**%**
	½	**¾**	**1**	**1½**	**2**		
low	30	29	26	30	15	130	96.3
medium	0	1	4	0	0	5	3.7
high	0	0	0	0	0	0	0.0
Total	30	30	30	30	15	135	100.0

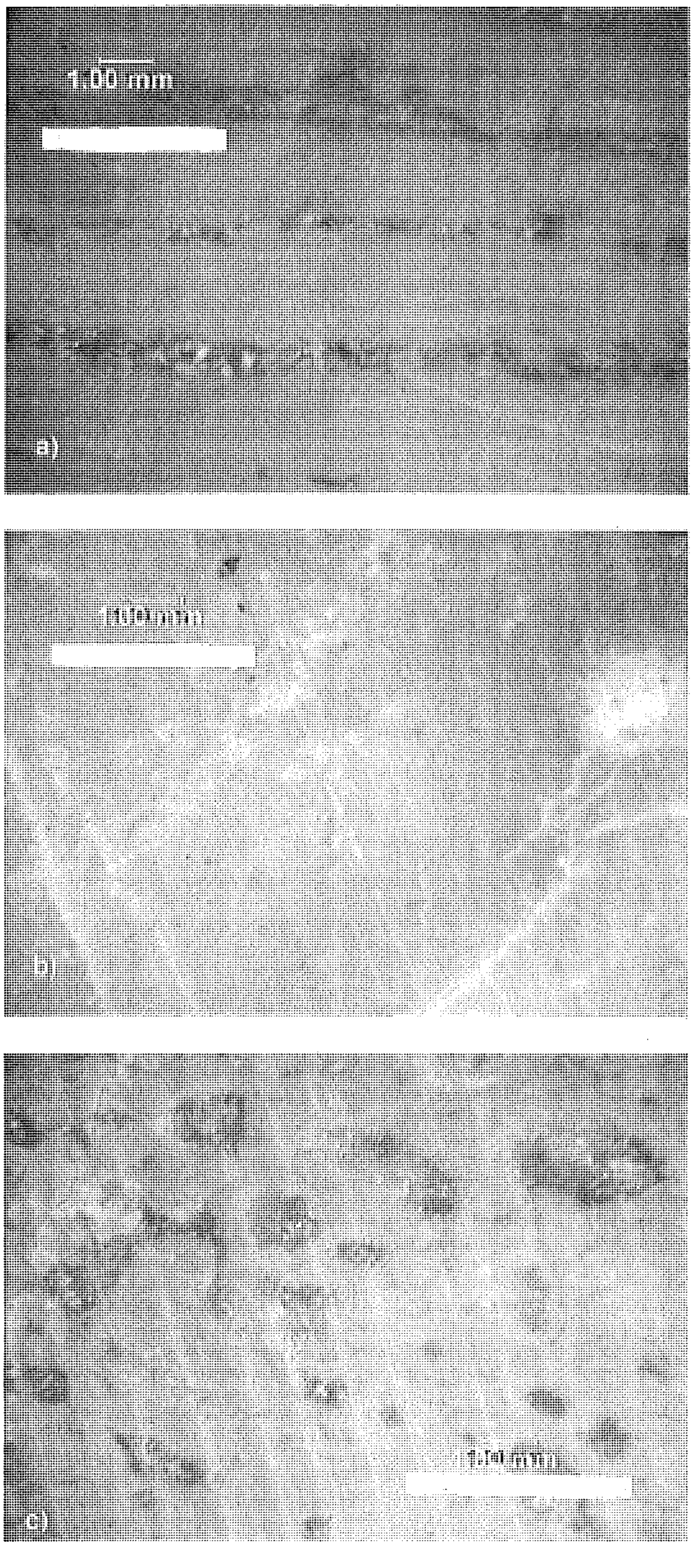


Figure 3.9.1 Source variability in Limestone 3. Magnification 13X. a) Beige-Brown with fine fenestral texture b) Beige-Brown Limestone, and c) Light Beige-Brown Limestone with small filled voids.

3.10 METAGABBRO 1

Metagabbro 1 is located in a slightly metamorphosed gabbroic rock (metagabbro) that occurs as part of the Canadian Shield. The intrusion is of Pre-Cambrian age. Aggregates from the quarry have mottled dark green to black and dark gray color. The metagabbro is fine-grained and has a Mohs scratch hardness of 5 to 6 (R. Muethel, MDOT).

3.10.1 Aggregate Subtypes

The representative sample consisted entirely of metagabbro (Table 3.10.1 and Figure 3.10.1). The metagabbro occasionally was cut by fine 0.04 inch calcite veinlets. The field sample contained a few calcite veinlets exposed as coatings on some of the particles. However, none of the particles picked for petrographic examination had any exposed calcite veinlets. Cracks were observed in 17.8% of the particles with the majority of the cracked material retained on the 1 inch sieve size.

Table 3.10.1 Petrographic Observations of Aggregate Particles from Metagabbro 1.

Crushed Stone	**Sieve Size (inch)**						
Subtype	**½**	**¾**	**1**	**1½**	**2**	**Total**	**%**
Metagabbro	30	30	30	30	15	135	100.0
number of aggregates with cracks	3	4	12	5	0	24	17.8
number of aggregates with coatings$	0	0	0	0	0	0	0.0

$ calcite veinlets

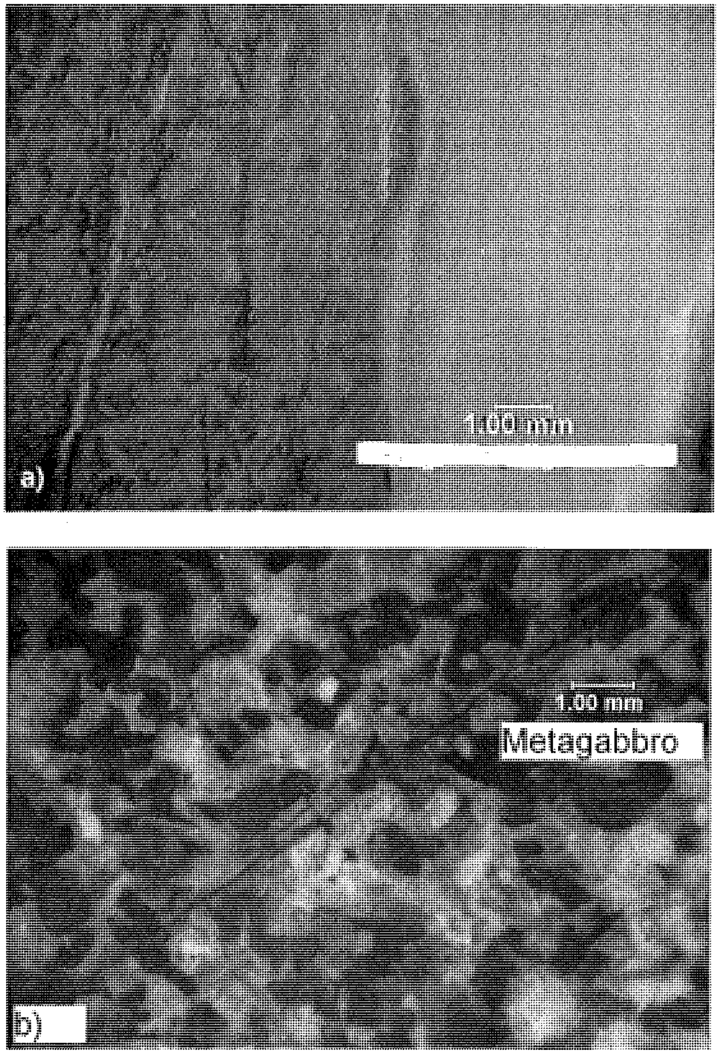


Figure 3.10.1 Examples of Aggregates in the Metagabbro 1 Source: a) metagabbro with calcite veinlet; b) metagabbro.

3.10.2 Relative Micro-Porosity

The particles in this aggregate source all have a very low micro-porosity (Table 3.10.2).

Table 3.10.2 Evaluation of Micro-Porosity of Aggregates from the Metagabbro 1 Source

Micro-Porosity	**Sieve Size (inch)**					**Total**	**%**
	½	**¾**	**1**	**1½**	**2**		
low	30	30	30	30	15	135	100.0
medium	-	-	-	-	-	0	0.0
high	-	-	-	-	-	0	0.0
Total	-	-	-	-	-	0	100.0

3.11 PETROGRAPHIC SUMMARY OF AGGREGATE SOURCES

The petrographic analysis showed that the primary particles present in the aggregate sources, except Metagabbro 1 were dolomite, limey dolomite, dolomitic limestone, or limestone, occasionally with minor amounts of shale and/or coral. The Metagabbro 1 source contains silicate rock material. The aggregates from all the sources are produced by crushing the mined rock material resulting in angular shapes. A summary of the major petrographic characteristics of each of the aggregate sources is given in Table 3.11.1.

Table 3.11.1 Summary of Petrographic Findings

Source	Dol 1	Dol 2	Dol 3	Dol 4	Lime 2	Lime 3	Dol 5	Met 1	Lime 1	Dol 6
Number of aggr. subtypes	4	8	8	5	2	2	6	1	4	2
Rock subtypes										
Dolomite/limey dolomite	100	91.5	98.5	100	-	-	98.6	-	-	100
limestone/dolomitic limestone	-	-	-	-	100	100	-	-	99.3	-
% shaly dolomite	-	1.4	-	-	-	-	0.7	-	-	-
% shale	-	7.1	-	-	-	-	-	-	-	-
% coral	-	-	-	-	-	-	0.7	-	0.7	-
% metagabbro	-	-	-	-	-	-	-	100	-	-
% with cracks	63.0	43.6	25.0	49.6	24.3	33.3	35.0	17.8	35.6	32.8
% with coatings	25.9	15.7	24.3	21.5	33.9	-	7.4	-	23.7	15.3
Micro-porosity										
% low	88.9	67.9	48.5	30.4	84.3	96.3	75.9	100	61.5	98.5
% medium	9.6	25.7	31.6	43.7	15.7	3.7	19.0	-	32.6	1.5
% high	1.5	6.4	19.9	25.9	-	-	5.1	-	5.9	-

- : not observed in laboratory sample

3.11.1 Source Homogeneity

Despite the apparent homogeneity of aggregate batches when classified by rock-type, several subtypes can be defined through second order classification due to different colors, textures, bedding, the presence of shale, etc. (Table 3.11.1). Most of the sources contain between 1and 5 aggregate subtypes. Sources Dolomite 2, Dolomite 3, and Dolomite 5 are the most inhomogeneous sources and contain between 6 and 8 different aggregate subtypes. In addition to the presence of different dolomite subtypes, the presence of shale and bedded dolomite also contributes to the inhomogeneity of these three sources.

3.11.2 Cracks and Rock Coatings

Cracks, bedding, and coatings can be the origin for freeze-thaw disintegration of the aggregate and may reduce the freeze-thaw performance of the concrete in which it is embedded. Cracks can either be originally in the rock due to the presence of faults, joints and weak bedding planes, or they can be due to crushing of the original rock into the suitable aggregate sizes. Micro-cracks were observed in more than 40% in the samples from Dolomites 1, 2 and 4, (Table 3.11.1. and Figure 3.11.1). The lowest number of cracked aggregates (17.8%) was observed in the metagabbro 1 source.

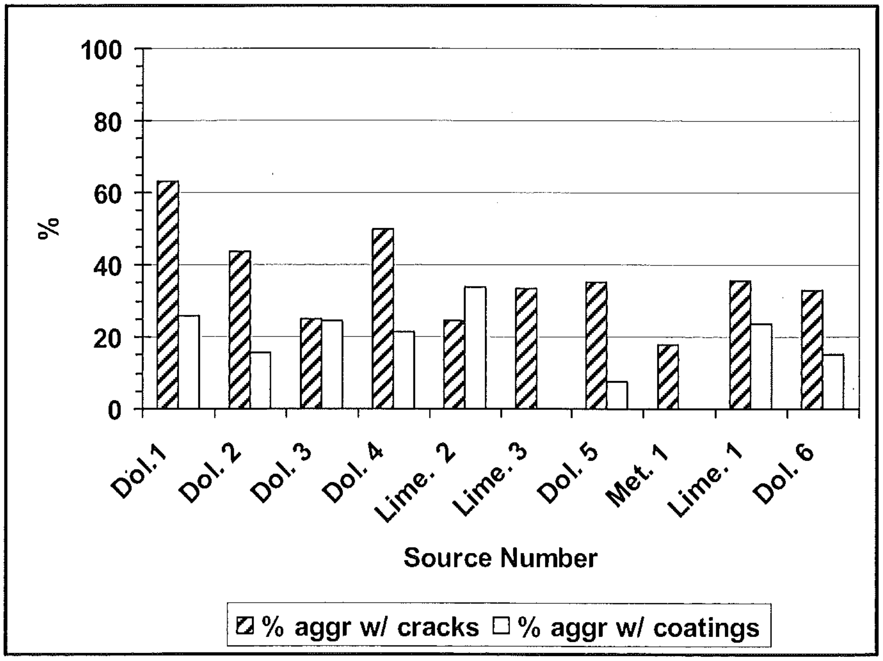


Figure 3.11.1 Diagram Showing the Percentage of Aggregates that Contain Primary Cracks and Coatings in Each of the Aggregate Sources used in the Study.

Coatings can cause freeze-thaw deterioration of the concrete by detachment of the aggregate from the binder material and subsequent crack propagation into the concrete matrix. Coatings were usually less abundant than cracks (Table 3.11.1. and Figure 3.11.1). The maximum number of coated aggregates (33.9%) was observed in source

Limestone 2, whereas no coatings were observed in Limestone 3 and Metagabbro 1. The number of aggregates with coatings was also low in Dolomite 5 (7.4%). Between 15.3% and 25.9% of the aggregates in the other sources contained coatings.

CHAPTER 4 – CONFINED FREEZE-THAW TESTING OF FULLY SATURATED COARSE AGGREGATE

This chapter presents the results and discusses the major findings obtained from the confined freeze-thaw tests on concrete beams fabricated with a large aggregate gradation (2.5 inch maximum size) and with a regular size (Series 6) coarse aggregate gradation. The coarse aggregates were moisture conditioned by vacuum saturation prior to concrete batching. Beams containing the 2½ inch maximum aggregate size were 6 by 6 inches in cross section and 15.5 inches long were made and tested at the U of Michigan, Ann Arbor. Concrete beams containing Series 6 (i.e. 1 inch maximum aggregate size) coarse aggregate gradation with dimensions of 3 by 4 inches by 15.5 inches were fabricated and tested at the Lansing MDOT Construction and Technology Laboratory.

4.1 Results from Confined F-T Testing

Table 4.1 lists the summary F-T test results and key aggregate and fresh concrete properties for the ten investigated aggregate sources. The average air content of the fresh concrete mixes ranged from 6.4 to 7.5% for the Series 6 mixes, and 5.2 to 7.4% for the large aggregate gradation. The dilation for the Series 6 beams ranged from 0.002 to 0.077 % per F-T 100 cycles. The dilation for the large aggregate gradation ranged from 0 to 0.369 % per F-T 100 cycles.

Minimal to no surface cracking developed in the beams made with the three large aggregate gradation sources with the lowest vacuum saturated absorption values (0.36% - 0.65%). The remaining seven large aggregate gradation sources developed visible beam cracking. Five sources (dolomite sources 2, 3, 4 & 5 and limestone source 1) developed moderate (surface crack width less than 0.04 inches) to severe (>0.04 inches) surface cracking. These sources had vacuum saturated absorption values ranging from 2.19 to 3.99 percent. The three sources with the highest vacuum saturated absorption values developed rapid beam failure (< 100 F-T cycles).

After F-T testing, the beams were cut across cracked areas. These cross sections revealed that cracking was most pronounced around large (2-2.5 inch) highly micro-porous particles. The localization of cracking around highly F-T susceptible coarse aggregate is consistent with high aggregate expansion during freezing of pore water resulting in mortar cracking. Internal volumetric aggregate expansion in concrete increases rapidly with aggregate size. Therefore, mortar cracking is more pronounced around the largest aggregate with high F-T susceptibility. These factors (aggregate size and absorption) are discussed further in chapter 6 as part of the major project objective to develop a transfer function for predicting dilation of the large aggregate gradations from F-T dilation results and other aggregate characteristics (such as absorption) for the Series 6 gradation.

The beam shown on the left in Figure 4.1 is a typical example of the most severe beam cracking observed in this project (dolomite 4 source large aggregate gradation). Dolomite 4 source is inhomogeneous with eight sub-categories of dolomite rock types in the coarse aggregate. Further, the largest aggregate particle in Figure 4.1 was found to be highly micro-porous and is one of the eight identified sub-categories. The beam on the right hand side in Figure 4.1 is a typical example of the best performing source (metagabbro 1) aggregate source. This source is homogeneous with one aggregate type of low absorption (0.36%).

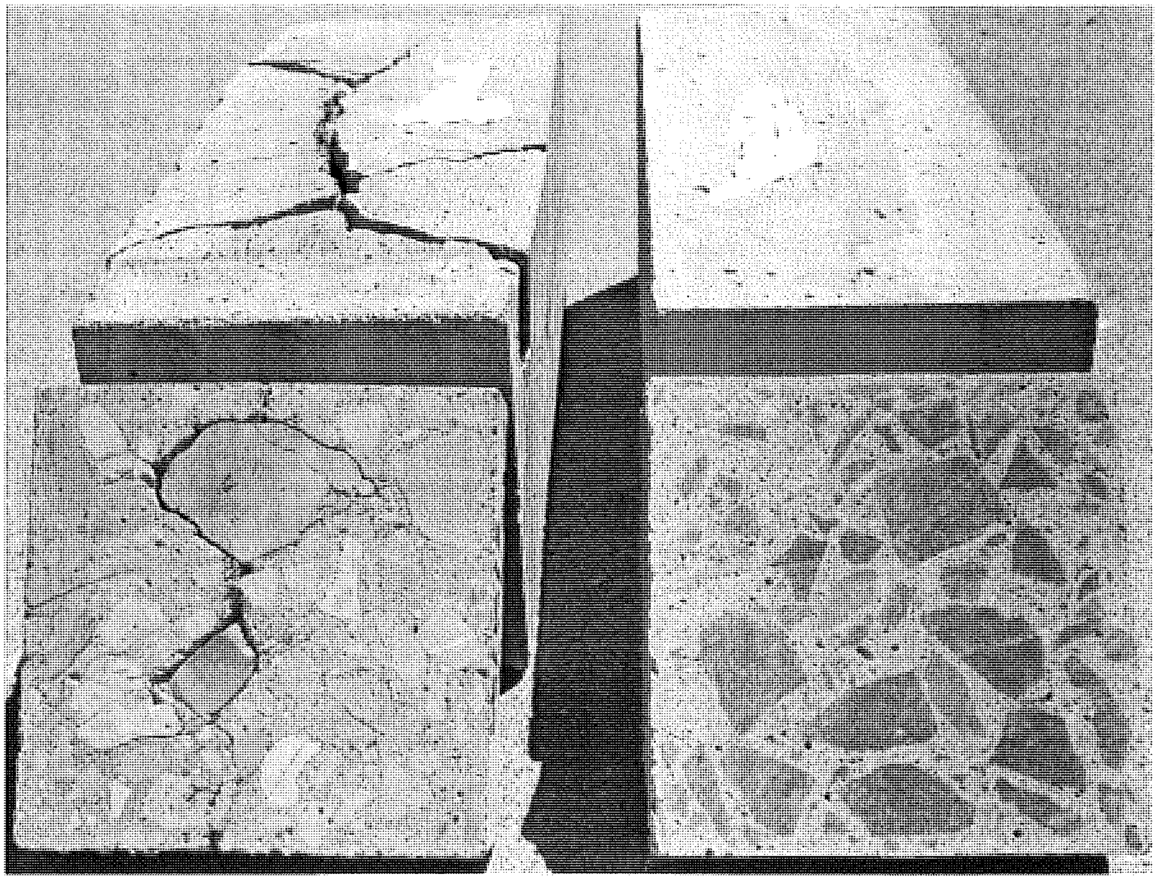


Figure 4.1 Dolomite 4 source after less than 100 F-T cycles, and metagabbro 1 source after 300 F-T cycles.

Table 4.1 Summary Coarse Aggregate and Concrete Beam Test Results & Cracking Observations.

	Series 6 Aggregate						Large Aggregate Gradation			
Agg. Type	Unit Wt. lbs/cyd (Dry Loose)	Specific Gravity (Bulk Dry)	24 hour Soak %	Abs. Cap. 24 hour . Vac. Sat (%)	Fresh Conc. Air Cont. % (Ave.)	Ave. Beam Exp. %/100 F-T cyc	Fresh Conc. Air Cont. % (Ave.)	Ave. Beam Exp. %/100 F-T cyc.	Beam Cracking (Severe/Mod./Min. to None)	Major Cause of Cracking cracked beams
Dol. 1	100	2.79	0.49	0.65	6.8	0.002	5.9	0.003	Min.- none	localized mortar cracking from large aggregate near the surface
Dol. 2	87	2.65	1.91	2.74	6.9	0.003	7.4	0.079	Mod. - Seve.	fracture of large (2-2.5 in.) micro-porous gray dolomite
Dol. 3	90	2.57	2.92	3.71	6.4	0.077	5.6	0.369	Mod.- Seve.	fracture of large (2-2.5 in.) micro-porous gray dolomite
Dol. 4	89	2.56	3.06	3.99	6.7	0.037	5.3	0.293	Mod.- Seve.	fracture of large (2-2.5 in.) micro-porous mottled beige-brown dolomit
Dol. 5	93	2.67	1.47	2.19	7.5	0.007	5.2	0.162	Mod.- Seve.	fracture of large (2-2.5 in.) micro-porous gray dolomite
Dol. 6	100	2.81	0.39	0.47	7.2	0.004	6.2	0.000	Min-None	mortar delamination around large aggregate near free surface
Lime. 1	93	2.52	1.43	2.60	6.9	0.015	5.7	0.067	Mod.- Seve.	fracture of large (2-2.5 in.) brown and beige-brown limestone
Lime. 2	90	2.57	1.20	2.04	7.0	0.016	5.8	0.095	Mod.	fracture of large (2-2.5 in.) brown limestone
Lime. 3	96	2.66	0.66	0.84	7.4	0.009	5.7	0.019	Mod.	fracture of large (2-2.5 in.) beige-brown limestone
Met. 1	94	2.88	0.33	0.36	7.5	0.002	5.9	0.000	None	-

CHAPTER 5 – UNCONFINED FREEZE-THAW TESTING OF COARSE AGGREGATE

5.1 Results

In this chapter, the F-T testing results of unconfined (i.e. aggregate particles) loose large aggregate and Series 6 are presented and briefly discussed. The mass-loss for each source is determined after 300 freeze-thaw cycles. Series 6 coarse aggregate was tested according to the procedure outlined in MTM 124-99. The large aggregate gradation particles required a much greater initial mass, therefore it was decided to modify MTM 124-99. Only the broken-off pieces were used to determine the mass-loss for a given size. This was justified since only flaked particles were found. In this procedure, the coarse aggregate particles were moisture conditioned by soaking for 24 hours in water at room temperature prior to F-T testing. This differs from the moisture conditioning used in confined F-T testing.

Unconfined F-T mass-loss results are shown in Tables 5.1.1 and 5.1.2 for the large aggregate blend and the Series 6 coarse aggregate following 300 F-T cycles.

Table 5.1.1 Mass-Loss in Percent from Unconfined F-T Testing of Large Aggregate Blend for Investigated Aggregate Sources.

Sieve	**Dol. 1**	**Dol.2**	**Dol. 3**	**Dol. 4**	**Lime. 1**	**Lime. 2**	**Lime. 3**	**Dol. 5**	**Dol. 6**	**Met. 1**
1/2 inch	0.01	0.81	1.95	0.36	1.27	0.35	6.69	0.09	0.01	0.03
3/4 inch	0.02	5.02	11.27	6.78	0.05	0.41	0.48	3.53	0.02	0.01
1 inch	0.01	7.27	1.71	5.31	0.05	0.65	0.61	0.59	0.04	0.02
1-1/2 inch	0.01	5.48	5.07	16.35	0.07	0.31	0.33	0.23	0.00	0.00
2 inch	0.02	11.07	11.80	21.64	0.08	0.25	0.06	0.07	0.02	0.01
Ave% for sieves 0.5-2.0 i	0.014	5.931	6.360	10.089	0.305	0.395	1.635	0.903	0.019	0.013

Table 5.1.2 Mass-Loss in Percent from Unconfined F-T Testing of Series 6 Aggregate for Investigated Aggregate Sources

Sieve	**Dol. 1**	**Dol.2**	**Dol. 3**	**Dol. 4**	**Lime. 1**	**Lime. 2**	**Lime. 3**	**Dol. 5**	**Dol. 6**	**Met. 1**
No. 4	1.29	2.44	4.19	3.48	1.18	2.00	3.68	1.65	0.49	0.96
3/8 inch	0.72	2.88	4.03	3.27	0.90	1.38	5.27	1.35	0.34	0.50
1/2 inch	0.40	2.54	2.46	3.44	0.82	1.19	5.60	1.53	0.24	0.38
3/4 inch	0.35	3.49	5.71	2.69	1.18	1.12	4.41	0.80	0.17	0.21
Ave. % for sieves no.4-3/4 in.	0.69	2.84	4.10	3.22	1.02	1.42	4.74	1.33	0.31	0.51

The large aggregate and Series 6 gradations can be divided into three categories of mass-loss ranging from high to medium to low. These results are shown in Figure 5.1.1 a, b, and c. The high category aggregates are characterized by having greater mass loss with increasing aggregate size with average mass-loss greater than 5% for the large aggregate gradation. The low category aggregates have less than 1 percent average mass-loss regardless of size.

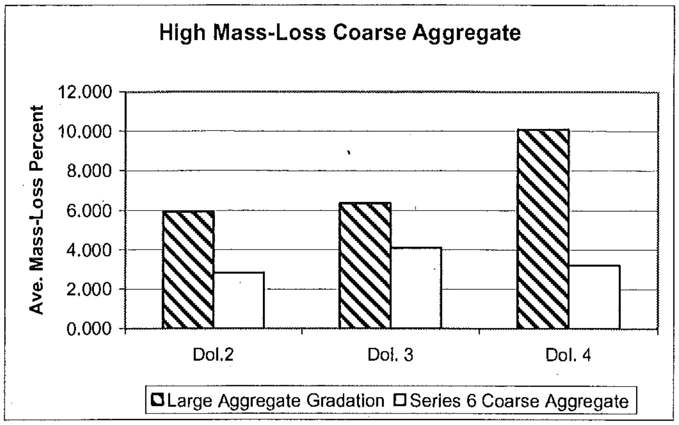


Figure 5.1.1 a. High Mass-Loss Coarse Aggregate for the Large Aggregate and Series 6 Gradations.

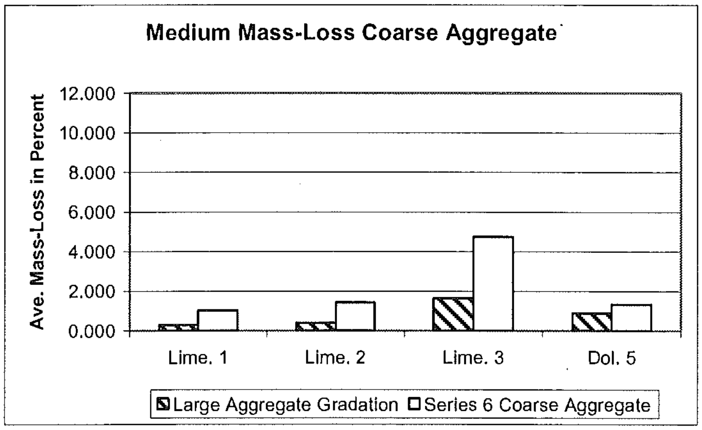


Figure 5.1.1 b. Medium Mass-Loss Coarse Aggregate for the Large Aggregate and Series 6 Gradations.

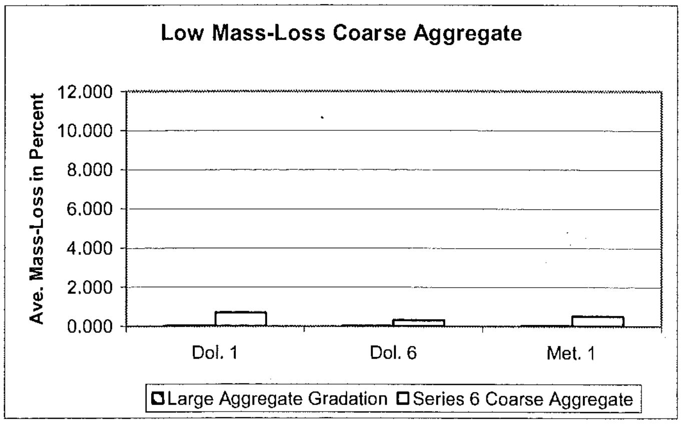


Figure 5.1.1 c. Low Mass-Loss Coarse Aggregate for the Large Aggregate and Series 6 Gradations.

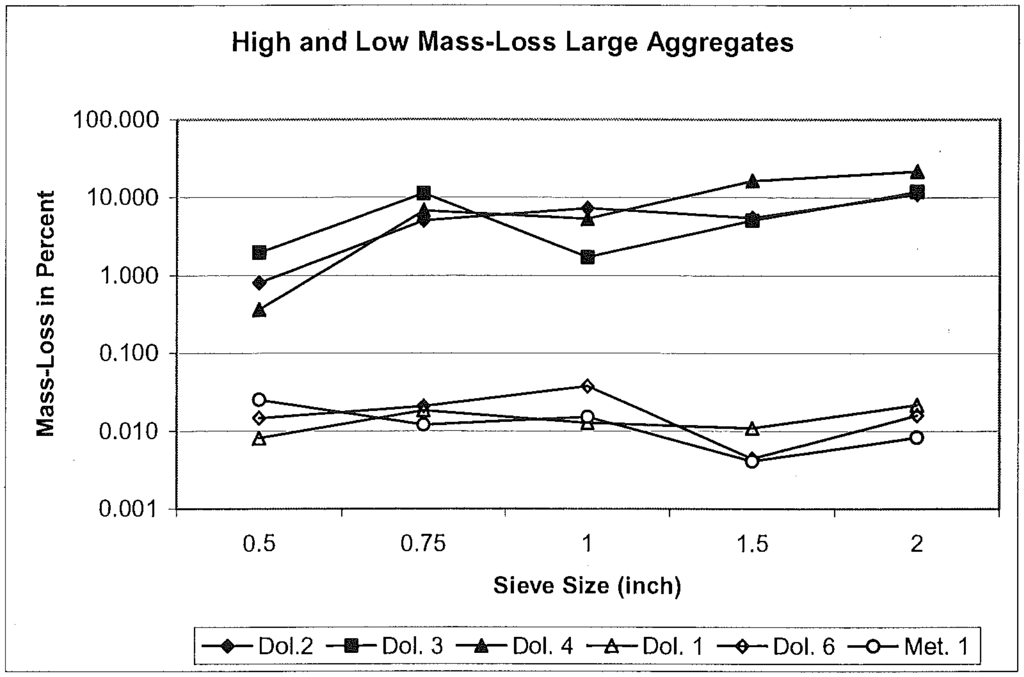


Figure 5.1.2 High and Low mass-loss large coarse aggregate.

Figure 5.1.2 shows that the Unconfined F-T mass-loss increases with increasing aggregate size for the high category, whereas mass-loss is not affected by aggregate size for the low category. Note the two to three orders of magnitude difference in mass-loss between these two groups and that mass-loss is increasing by a factor of 10 between sieve sizes 0.5 inch and 2 inch for the high category. This is consistent with a known D-cracking mechanism where entrapped water cannot escape during freezing resulting in internal stress build-up. As the water freezes, internal stresses reach critical values resulting in damage to the aggregate particle. This damage is exhibited by the mass-loss and increases with increasing path-length and aggregate size.

In summary, the high mass-loss test results for the large aggregate gradation corresponds with moderate to severe beam cracking in the confined F-T specimens, and low mass-loss test results corresponds with little or no beam cracking.

CHAPTER 6 – DILATION OF SATURATED COARSE AGGREGATE DURING A SINGLE FREEZING AND THAWING CYCLE

6.1 Introduction

To better understand the F-T results presented in Chapters 4 & 5, a series of dilation-temperature measurements were conducted on selected aggregate samples.

6.2 Background

It is generally agreed that the properties of aggregates affecting frost resistance include pore size, porosity, permeability, size, strength, and moisture condition. A worst case scenario is achieved when the aggregate is critically saturated. It is also generally agreed that the F-T mechanisms, although still not fully understood, may be explained using the hydraulic pressure theory developed by Powers and coworkers in the 1940s and 1950s.

For a given source which is D-cracking susceptible, (i.e. F-T durability improves with decreasing maximum aggregate size) increased deterioration is expected with increased particle size. Powers and Helmuth [12] developed the concrete dilation test that is the basis for ASTM C 671. He concluded that dilation versus cooling temperature tests allow a direct assessment of the coarse aggregate frost resistance and concrete's D-cracking susceptibility. It quantifies, at a given saturation level, the expansive nature of an aggregate as the water freezes.

Critically saturated coarse aggregate expansion must generate less strain than the tensile strain of the mortar for concrete to be frost resistant. In the work by Buck [13] titled "Evaluation of the Frost Resistance of Concrete Using Critical Dilation," it was concluded:

1) Concrete is frost resistant if the dilation from a single F-T cycle is less than 50 micro-strain

2) Concrete is not frost resistant if the dilation from a single F-T cycle equals or exceeds 200 micro-strain

3) Additional cycles of freezing are needed to assess frost resistance of concrete for dilation values in between these.

The remaining portion of this chapter presents the results and discusses the major findings obtained from the unconfined coarse aggregate dilation test. The coarse aggregate sample was moisture conditioned by vacuum saturation prior to testing in the dilation apparatus. To minimize moisture loss during the F-T test, the specimen was wrapped in thin plastic. The cooling and heating rate was constant at 0.9 F/minute. Section 2.6 of this report outlines the details of the test and apparatus.

6.3 Major Results

6.3.1 Aggregates with High Expansion.

Figure 6.3.1 is an example of an aggregate type within a source, which was found to develop severe F-T damage in the concrete beams. As seen in this figure, a sudden expansion of 1000 micro-strain occurs when the pore water freezes. This is far greater than the 200 micro-strain that Buck found caused cracking in concrete. The results also show that the specimen does not return to its original length at the conclusion of the test, which indicates permanent expansion. This expansion suggests internal damage. Similar behavior was found in dolomite Sources 3, 4 and 5 for selected aggregate subtypes which were found to cause beam cracking.

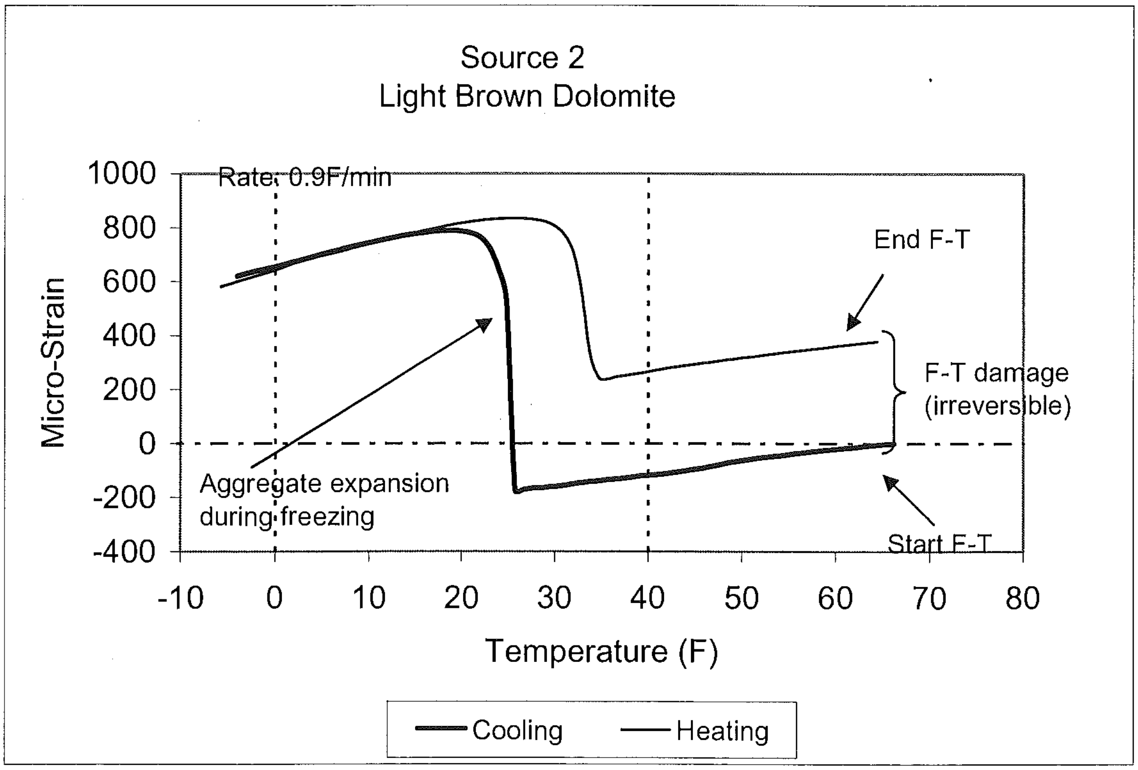


Figure 6.3.1. Aggregate dilation during first F-T test. Highly F-T susceptible dolomite particle representing 32.1% of the large aggregate sample from Source 2.

6.3.2 Aggregate Sources with Moderate F-T Expansion.

Figure 6.3.2 is an example of an aggregate subtype within a source, which was found to develop moderate F-T damage in the concrete beams. As seen in this figure, a sudden expansion of about 75 micro-strain occurs when the pore water freezes. This is greater than the 50 micro-strain that Buck found was the upper value to be frost resistant. Buck also concluded, that for values lying between 50 and 200 micro strain more than one F-T cycle is necessary to determine frost resistance. The results show that the specimen nearly returns to its original length at the conclusion of the test, which indicates little damage. Additional cycling may produce more damage. Similar behavior was found in both aggregate subtypes within limestone Sources 1 and 2, and in an aggregate subtype corresponding to 16.8% of dolomite Source 5.

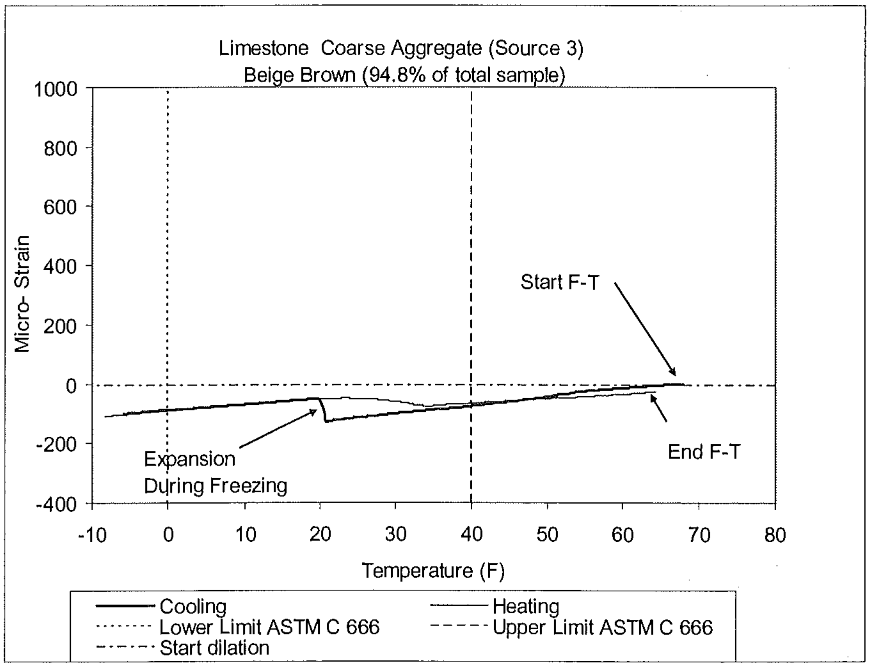


Figure 6.3.2 First F-T dilation of beige brown aggregate (94.8% of total sample) from limestone Source 3 belonging to the moderate F-T category.

6.3.3 Aggregates with Low F-T Expansion.

Typical F-T length change curves for Dolomites 1, 6, and Metagabbro 1 sources are shown in Figures 6.3.3 and 6.3.4. These sources developed less than 50 micro-strain expansion upon freezing of pore water and returned to the original specimen length after the test. This would indicate no permanent damage, and is consistent with the findings by Buck, that these aggregates are frost resistant. Visual examination of the beams after F-T testing revealed minimal or no cracking, and confirmed their frost resistance. These sources were found to be more homogeneous than the medium and high expansion categories, and of low absorption (< 1%).

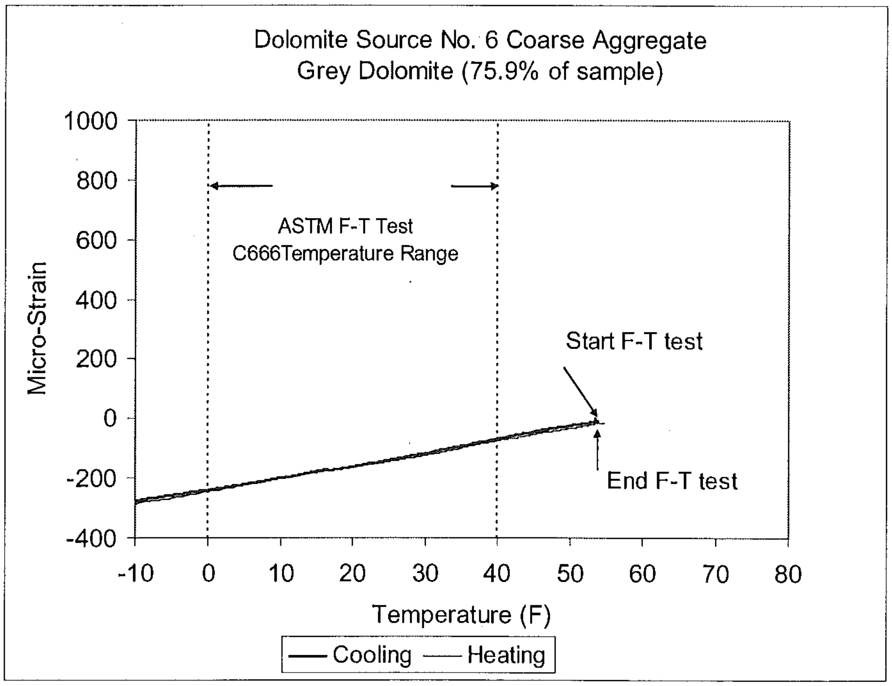


Figure 6.3.3 Length change of saturated grey dolomite coarse aggregate from Dolomite Source 6.

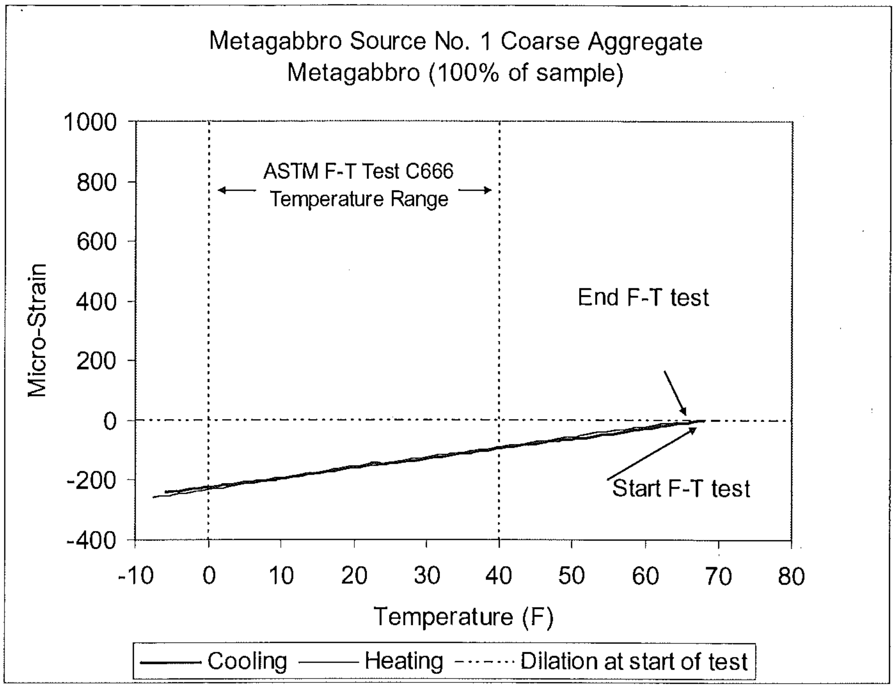


Figure 6.3.4. First F-T response of saturated Metagabbro Source 1 large coarse aggregate.

CHAPTER 7 – DATA ANALYSIS FOR TRANSFER FUNCTION

7.1 Project Objective

This study's primary objective is to develop, if possible, a transfer function between test results from MDOT's existing Series 6 F-T testing program and large coarse aggregate gradations from the same sources. A transfer function would make it possible for MDOT to estimate durability ratings for large aggregate sources based on standard Series 6 ratings.

7.2 Data Analysis.

Figure 7.2.1 shows a general trend between percent expansion values for the beams containing the Series 6 and the large aggregate gradations. The distribution of test results does not follow one trend. This suggests that percent expansion alone is inadequate for determining a transfer function.

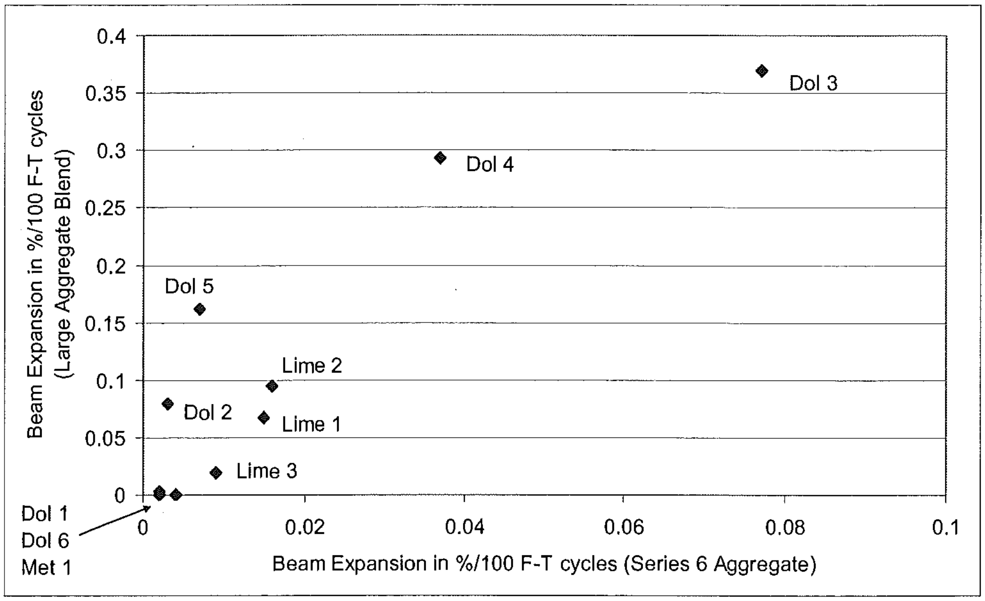


Figure 7.2.1 F-T expansion of concrete with Large Aggregate Blend versus Series 6 Aggregate.

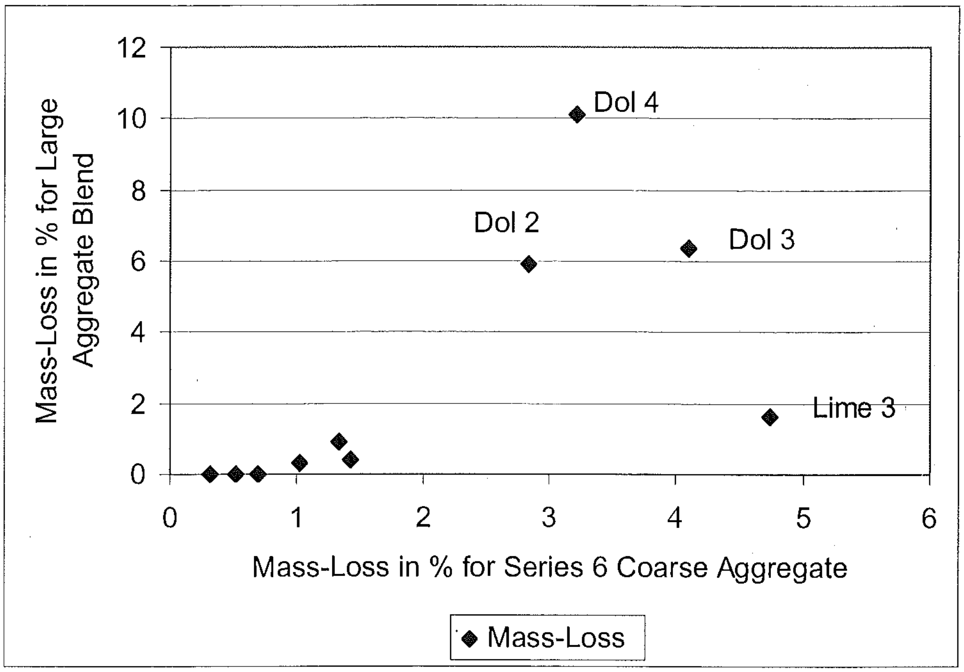


Figure 7.2.2 Average Mass-Loss for Large and Series 6 Coarse Aggregate Gradation.

Figure 7.2.2 presents mass-loss values for the aggregates containing the Series 6 and the large aggregate blend. The pronounced upward trend is due to Dolomites 2, 3 & 4. The mass-loss of these sources was higher than any of the other aggregate sources tested, and this mass-loss increased with aggregate size as seen in Figure 5.1.2. Similar to beam expansion results, mass-loss results for Series 6 coarse aggregate are inadequate for determining a transfer function.

Figure 7.2.3 shows a good general trend between percent expansion versus 24 hour absorption for the beams containing the Series 6 and the large aggregate gradations. A logarithmic scale is used to illustrate the wide range in beam dilation results for the 10 different aggregate sources. Large beam results for two sources (Dol 6 and Met 1) are not shown due to zero beam expansion. The results illustrate that large aggregate beam expansion increases several fold with increasing 24 hour absorption, and that only aggregate sources of absorption (<1%) develop F-T expansion values below the current MDOT threshold. This limits the usefulness of any transfer function as only the high quality coarse aggregate can produce F-T resistant concrete for large aggregate size (2.5 inch).

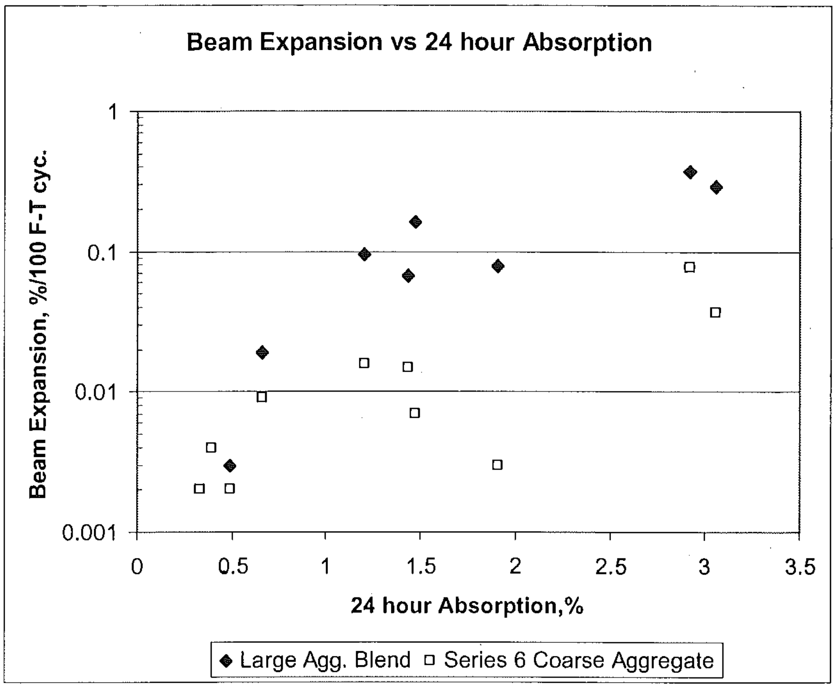


Figure 7.2.3 Beam expansion in F-T versus 24 hour absorption for the large aggregate blend and the Series 6 aggregate.

Source homogeneity is a major factor which limits the use of moderate F-T durable aggregate sources. A case in point is the Dol. 5 source. It contains several different aggregate subtypes of widely different expansion- porosity (absorption capacity) characteristics as seen from Figure 7.2.4. The grey tan mottled bioturbated aggregate subtype, which constitutes 73.1% of the aggregate source, has an absorption capacity (AC) of 2.1%. The expansion on freezing is about 600 micro-strain, which according to Buck (13) would result in beam cracking. The highly porous (8.8% Absorption Capacity) tan massive crystalline coarse aggregate on the other hand has less than 100 micro-strain expansion as water freezes. It was observed from the F-T test in the dilatometer that water accumulated on the surface of the aggregate during freezing, indicating that this aggregate type is very permeable and thus can expel water during freezing, which limits the internal stress causing aggregate expansion.

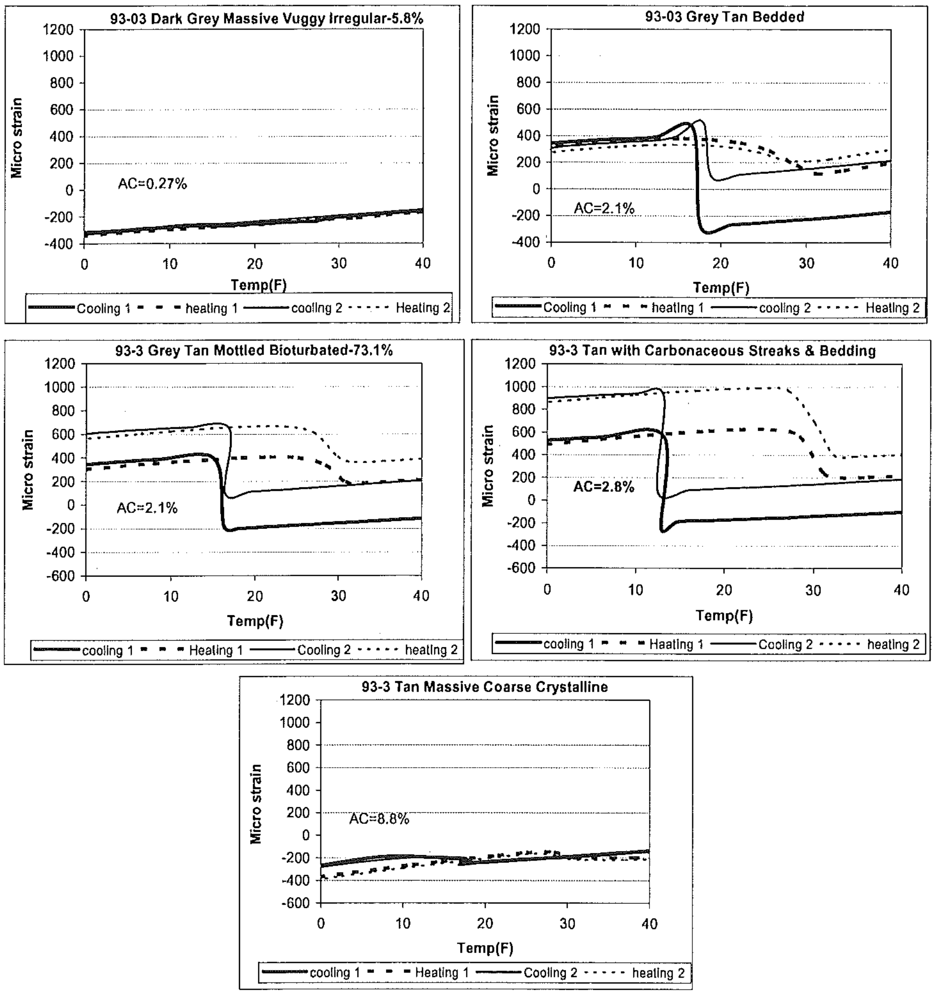


Figure 7.2.4 Coarse aggregate strain versus temperature curves for different aggregate types found in Dol. 5 source subjected to two F-T cycles in the saturated condition.

Visual observation of cracked beams from the Dol.5 source showed substantial damage in and around the large grey dolomite particles. Figure 7.2.5 illustrates this.

Figure 7.2.5 Example of cross section one of the most severely cracked beam (Dolomite Source 5 Batch 1, beam 2).

Therefore, source inhomogeneity may cause large differences in beam expansion due to the random location of large coarse aggregate of poor F-T characteristics. This is illustrated in Figure 7.2.6 for the Dol. 5 source. The coefficient of variation in large aggregate beam expansion from F-T ranged between 30 to 60%. Once cracking starts the F-T damage accelerates for every additional F-T cycle.

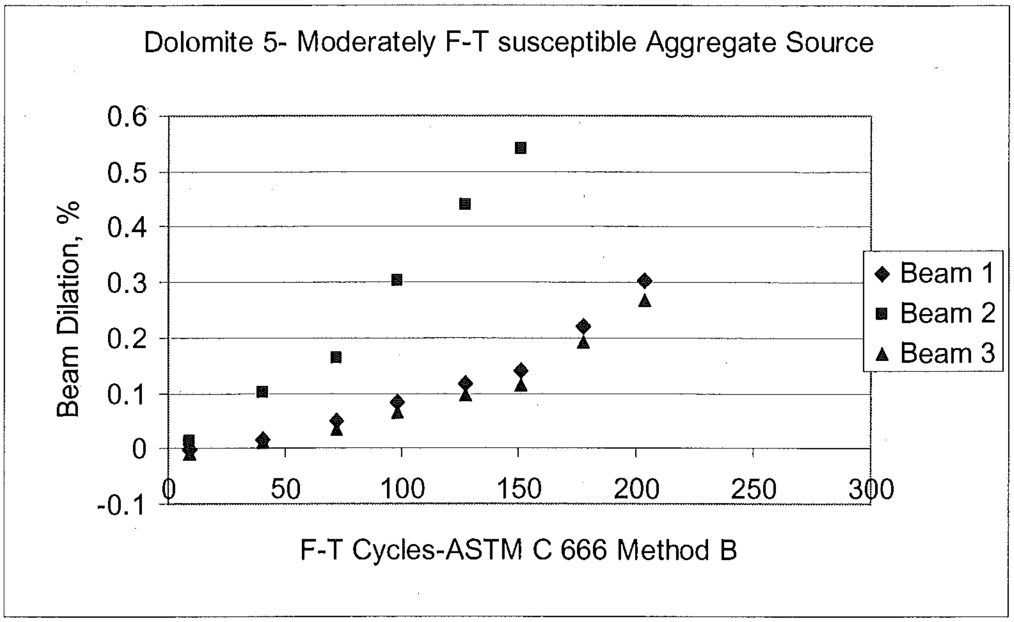


Figure 7.2.6 . Large-aggregate beam dilation versus number of F-T cycles (Dolomite Source 5).

CHAPTER 8 – CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

- This study's results show the risk of F-T failure is low for large aggregate blends when the source of the large aggregate has near zero (<0.010%) beam expansion per 100 cycles for Series 6, and is homogeneous. On the other hand, even if the source has low expansion for Series 6 but is inhomogeneous (i.e. contains several sub-categories), the risk of F-T failure for the large aggregate blend is increased.

- No single F-T transfer function was obtained based on the results of this study. The reason for this was the widely different F-T response. Some aggregate sources had near zero F-T expansion at any size while other aggregate sources had different F-T behaviors as the aggregate size increased. Although the aggregate sub-categories were found to exhibit substantial differences in expansion upon freezing, these differences were not controlled only by absorption capacity or relative micro-porosity. Other factors such as shaley bedded layers, mottling and micro-cracks developed during aggregate processing can contribute to poor F-T performance.

- Poorly performing coarse aggregate sources (dolomites 2, 3 & 4) in this study were found to have D-cracking characteristics. The large aggregate F-T beams from these sources developed cracks after only a few cycles. Visual examination of these beams after testing showed that the poorly performing aggregates were the 2 inch plus particles within these sources, and underwent significant internal damage. These sources had a 10 fold increase in mass-loss between the Series 6 and the large aggregate blend. The expansion values of the large aggregate beams were significantly higher than the Series 6. In addition, low temperature dilation tests on selected aggregate from these sources, exceeded by several fold the maximum tensile strain which was found by Buck, (13) to cause cracking. This supports the earlier findings by PCA that reducing the maximum aggregate size reduces the expansion.

- Three aggregate sources showed excellent F-T performance with near zero beam expansion in both the large aggregate blend and in Series 6. These sources are the Dol 1, Dol 6 and Met 1. Two common characteristics of these sources are homogeneity and low vacuum saturation absorption capacity (<0.7%).

- Source inhomogeneity within the moderate F-T category is a major risk factor when increasing the top size from 1 inch to 2.5 inches. The Dol. 5 source contained several different aggregate subtypes of widely different expansion upon freezing and porosity (absorption) characteristics. The results from this investigation suggest that the aggregate subtypes with greatest expansion due to freezing of pore water dominate the concrete F-T resistance, which in turn results in poor F-T performance in large aggregate blends. If such large size aggregates are used for a given project, even a small increase in the percentage of an aggregate subtype with high expansion, absorption and micro-porosity may significantly reduce F-T performance.

8.2 Recommendations

- In jointed concrete pavement (JRCP) applications high quality (<0.010% beam expansion per 100 cycles for Series 6, and is homogeneous) coarse aggregate of large particle size (1 to 2.5 inches) ensure excellent long-term F-T durability and excellent joint/crack performance. Three of the ten aggregate sources investigated in this study are expected to meet both criteria (Dol 1, Dol 6 and Met 1).

- As an alternative, blending Series 6 gradation coarse aggregate in this study's moderate F-T category with high quality large aggregate is an option. Four of the ten sources in this investigation were found to be in the moderate F-T category (Limestones 1, 2, 3 and Dolomite 5).

- Neither visual inspection nor absorption capacity value for the aggregate provide definitive answers with respect to F-T resistance. Developing a rapid test procedure based on a single F-T cycle of the aggregate in a confined or unconfined condition, which determines the specimen dilation (micro-strain) associated with freezing of pore water, is recommended.

- Coarse Aggregate Freeze-Thaw durability rating, using confined Freeze-Thaw testing according to (MTM) 113, 114 and 115 should be continued for Series 6 gradation. Any future rapid test procedure to evaluate F-T resistance should be correlated with the existing test method.

- Future correlations may be appropriate between the existing confined freeze-thaw test for series 6 coarse aggregate and the current coarse aggregate unconfined test modified for moisture conditioning as specified in MTM 113.

CHAPTER 9- REFERENCES

1. Stark, D., P. Klieger (1973), "Effect of Maximum Size of Coarse Aggregate on D Cracking in Concrete Pavements", PCA, Bulletin RD, 023.01P.

2. Klieger, P., G. Monfore, D. Stark, W. Teske, (1974), "D-Cracking of Concrete Pavements in Ohio". Final Report, Ohio DOT-11-74.

3. Stark, D. (1976), "Characteristics and Utilization of Coarse Aggregates Associated with D-Cracking", PCA Bulletin, RD047.01P.

4. Schwartz, D.R. (1987), "D-Cracking of Concrete Pavements", NCHRP Synthesis of Highway Practice 134, Transportation Research Board, Washington, D.C., 34 pp.

5. "Method of Selection and Preparation of Coarse Aggregate Samples for Freeze-Thaw Testing," Michigan Test Method MTM 113-97, Michigan Department of Transportation, Lansing, Michigan, pp. 1-6.

6. "Method for Making Concrete Specimens for Freeze-Thaw Testing of Concrete Coarse Aggregate," Michigan Test Method MTM 114-95, Michigan Department of Transportation, Lansing, Michigan, pp. 1-6.

7. "Method of Testing Concrete for Durability by Rapid Freezing in Air and Thawing in Water Michigan Test Method MTM 115-97, Michigan Department of Transportation, Lansing, Michigan, pp. 1-5.

8. "Method for Determining Aggregate Durability by Unconfined Freezing and Thawing", Michigan Test Method MTM 124-97, Michigan Department of Transportation, Lansing, Michigan, pp. 1-5.

9. Talbot, A.N., and F.E. Richart (1923), "The Strength of Concrete: Its Relation to the Cement, Aggregate, and Water," Univ. Ill. Eng. Expt. Sta. Bull. 137. First development of the mortar-voids method of proportioning concrete, 118 pp.

10. "1996 Standard Specifications for Construction," Michigan Department of Transportation, Lansing, Michigan.

11. Muethel, R.W. MDOT, (Personal communication).

12. Powers, T.C. and R. A. Helmuth (1953) "Theory of Volume Changes in Hardened Portland-Cement Paste During Freezing", Proceedings, Highway Research Board, V. 32, pp. 285-297.

13. Buck, A.D.(1988) "Evaluation of the Frost Resistance of Concrete Using Critical Dilation," Cement, Concrete, and Aggregates, CCAGDP, Vol. 10, No.1, pp.48-50.

Ten Selected Quarried Coarse Aggregate Sources.

Name	Source No.	F-T Report
Cedarville	49-65	Dolomite 1
Ottawa Lake	58-03	Dolomite 2
Rockwood Stone	58-08	Dolomite 3
Denniston Farms	58-09	Dolomite 4
Michigan Limestone	71-03	Limestone 1
Presque Isle Stone	71-47	Limestone 2
Port Inland	75-05	Limestone 3
Silica	93-03	Dolomite 5
Manitoulin Dolomite	95-05	Dolomite 6
Bruce Mines	95-10	Igneous/Metamorphic (Trap Rock)- Met 1