2003-28

Final Report

Refinement And Validation Of The Hydraulic Fracture Test

Research

Technical Report Documentation Page

1. Report No. MN-RC 2003-28		2.		3. Recipients Accession No.	
4. Title and Subtitle Refinement and Validation of the Hydraulic Fracture Test				5. Report Date December 2003	
				6.	
7. Author(s) Rebecca A. Embacher and Mark B. Snyder				8. Performing Organization Report No.	
9. Performing Organization Name and Address University of Minnesota Department of Civil Engineering 500 Pillsbury Drive SE Minneapolis, MN 55455				10. Project/Task/Work Unit No.	
				11. Contract (C) or Grant (G) No. (c) 74708 (wo) 91	
12. Sponsoring Organization Name and Address Minnesota Department of Transportation 395 John Ireland Boulevard Mail Stop 330 St. Paul, Minnesota 55155				13. Type of Report and Period Covered Final Report	
				14. Sponsoring Agency Code	
15. Supplementary Notes http://www.lrrb.gen.mn.us/PDF/200328.pdf					
16. Abstract (Limit: 200 words) <p>The Washington Hydraulic Fracture test was developed under the Strategic Highway Research Program to address the need for a rapid, inexpensive test for concrete aggregate freeze-thaw durability. The original test and analysis procedures were not sufficiently reliable and accurate to merit widespread adoption and implementation. Several follow-up research efforts have been performed and each has resulted in improvements to the test. This report describes the results of recent research efforts to improve the test.</p> <p>The "hydraulic fracture index" has been replaced by a model that predicts freeze-thaw test dilation as a function of the distribution of particle mass retained on various sieves after testing. This model was developed using data obtained from freeze-thaw and hydraulic fracture testing of 18 quarried carbonate and gravel aggregate sources, and the resulting correlation is exceptional (r-squared = 0.98). In addition, a large test chamber was developed to allow testing of aggregate samples five times larger than the original small chamber, thereby allowing aggregate durability characterization with a single test run.</p> <p>It is believed that the hydraulic fracture test is now ready for more broad-based validation testing and eventual widespread acceptance and implementation as an accurate screening tool for concrete aggregate freeze-thaw durability.</p>					
17. Document Analysis/Descriptors				18. Availability Statement	
Freeze-thaw		Aggregate		No restrictions. Document available from: National Technical Information Services, Springfield, Virginia 22161	
Durability		Hydraulic fracture			
Concrete					
19. Security Class (this report) Classified		20. Security Class (this page) Classified		21. No. of Pages 209	
				22. Price	

REFINEMENT AND VALIDATION OF THE HYDRAULIC FRACTURE TEST

Final Report

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December 2003

Published by

Minnesota Department of Transportation
Research Services Section, MS 330
395 John Ireland Boulevard
St. Paul, MN 55155

This report represents the results of research conducted by the authors and does not necessarily represent the views or policy of the Minnesota Department of Transportation and/or the Center for Transportation Studies. This report does not contain a standard or specified technique.

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ACKNOWLEDGMENTS

The authors would like to express their appreciation to the Minnesota Department of Transportation (Mn/DOT) for their financial and technical support of the research described herein, including their efforts in performing the supplementary magnesium sulfate tests. Special thanks are offered to Karl Peterson, David Rettner, Nancy Whiting and Douglas Schwartz for their technical support and guidance.

The authors would also like to express their appreciation to Dr. Donald Janssen of the University of Washington Department of Civil Engineering, the originator of the Hydraulic Fracture Test concept, for his technical support and guidance on this project. Dr. Janssen also loaned the University of Washington's hydraulic fracture test equipment to the project team, which greatly expedited completion of the project test program.

Special thanks are also offered to the following people, all of whom were University of Minnesota student research assistants, for their efforts during the laboratory phases of this project: Joel Coudron, Anna Boenig, Tim Havlicek, Trevor Odden, Shane Ortlepp, Brandon Pierce, Sarah Schmidt, Michelle Boltjes, Nate Erpestad, Lindsey Handel, Nick Popehn, Jim Stremel and Dan Troolin. The successful completion of this project would not have been possible without their efforts.

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EXECUTIVE SUMMARY

“D”-cracking and other forms of aggregate-related freeze-thaw damage have often been associated with concrete pavements in Minnesota. The most widely accepted methods of evaluating aggregate freeze-thaw durability involve the preparation and freeze-thaw testing of concrete beams that contain the aggregate in question. These tests are generally time-consuming, sometimes requiring months to complete, and often require the use of expensive equipment and/or highly skilled operators. A more rapid test of aggregate freeze-thaw durability, called the Washington Hydraulic Fracture Test (WHFT), was developed by Dr. Donald J. Janssen (University of Washington) and Dr. Mark B. Snyder (formerly of Michigan State University). The WHFT equipment is relatively inexpensive and allows a single laboratory technician to assess the freeze-thaw durability of several samples of aggregate in as few as seven working days (1).

The WHFT simulates the effects of freeze-thaw cycles on saturated aggregate particles by forcing water into and out of the pore structure of dried aggregate particles in a water-filled pressure vessel. The water is forced into the aggregate pores using a pressurized nitrogen source, and rapid release of the pressure allows compressed air trapped within the aggregate pores to expand, expelling water from the aggregate and creating internal stresses similar to those produced during freezing and thawing. Aggregate fracture occurs when the aggregate pore structure does not allow rapid dissipation of the pore pressures and the aggregate particles are relatively weak. The amount of fracturing that results from this test has been shown to be an indicator of aggregate freeze-thaw susceptibility.

The WHFT was further developed under research efforts funded by the Michigan Department of Transportation (MDOT) in 1996 and the University of Minnesota Graduate College in 1997 (2, 3). These projects resulted in several refinements and improvements to the WHFT test apparatus and procedures and successfully demonstrated the potential value of the WHFT as a rapid freeze-thaw durability screening test for many concrete coarse aggregates. However, this research also resulted in the development of recommendations for test procedure changes and equipment

modifications that it was hoped would further reduce required testing efforts and might improve the reliability and interpretation of the WHFT results.

The primary objective of the current research effort was to improve the Minnesota Department of Transportation's (Mn/DOT's) ability to rapidly evaluate the potential freeze-thaw durability of coarse aggregate sources intended for use in portland cement concrete (PCC) pavement applications. This was to be accomplished by further refining the WHFT test apparatus and procedures and to validate them using aggregate samples obtained from Minnesota sources.

The most significant equipment and procedure modifications involve the development of a larger test chamber that allows the testing of a sufficiently large sample in a single test, and the development of models that accurately predict freeze-thaw test dilation as a function of the distribution of sample mass over various mechanical sieves following 50 WHFT pressurization cycles. The new equipment and procedures appear to offer better correlation with the results of rapid freezing and thawing tests than either the magnesium sulfate test (ASTM C88) or the current Mn/DOT absorption capacity criterion for carbonate aggregate sources.

Additional hydraulic fracture testing should be performed with the modified large hydraulic fracture test chamber using mass measurements and particle counts in the 19 to 38 mm (0.75 to 1.5 in) range to further validate the use of the large test chamber. Additional testing and research should also be performed to verify and determine the nature of the outlier hydraulic fracture test results, as described in the project report.

1. D. J. Janssen and M. B. Snyder, *SHRP C-391: Resistance of Concrete to Freezing and Thawing* (Washington, DC: Transportation Research Board, 1994).
2. M. B. Snyder, D. J. Janssen and W. Hansen, *Adoption of a Rapid Test for Determining Aggregate Durability in Portland Cement Concrete* (Ann Arbor, MI: University of Michigan Department of Civil Engineering, 1996).
3. J. J. Hietpas, *Refinement and Validation of the Washington Hydraulic Fracture Test* (Minneapolis, MN: University of Minnesota Department of Civil Engineering, 1998).

CHAPTER 1

INTRODUCTION

1.1 Research Objectives

The objective of the research described herein was to improve the Minnesota Department of Transportation's (Mn/DOT's) ability to rapidly evaluate the potential freeze-thaw durability of coarse aggregate sources intended for use in portland cement concrete (PCC) pavement applications. This was to be accomplished by refining the Washington Hydraulic Fracture Test (WHFT) and validating the apparatus and procedures using Minnesota aggregates.

1.2 Background

“D”-cracking and other forms of aggregate-related freeze-thaw damage have often been associated with concrete pavements in Minnesota. The best approach for preventing these types of distress is to avoid using aggregate sources that are known to be susceptible to freeze-thaw damage in concrete applications. The most widely accepted methods of evaluating aggregate freeze-thaw durability involve the preparation and freeze-thaw testing of concrete beams that contain the aggregate in question. These tests are generally time-consuming, sometimes requiring months to complete, and often require the use of expensive equipment and/or highly skilled operators. Furthermore, the variable nature of many aggregate sources necessitates frequent testing to ensure the adequate freeze-thaw resistance of material being produced at any given point in time.

A more rapid test of aggregate freeze-thaw durability was developed under the Strategic Highway Research Program (SHRP). This test, called the Washington Hydraulic Fracture Test (WHFT), was developed by Dr. Donald J. Janssen (University of Washington) and Dr. Mark B. Snyder (formerly of Michigan State University) (1). The WHFT equipment is relatively inexpensive and allows a single laboratory technician to assess the freeze-thaw durability of several samples of aggregate in as few as seven working days.

The WHFT simulates the effects of freeze-thaw cycles on saturated aggregate particles by forcing water into and out of the pore structure of dried aggregate particles in a water-filled

pressure vessel. The water is forced into the aggregate pores using a pressurized nitrogen source, and rapid release of the pressure allows compressed air trapped within the aggregate pores to expand, expelling water from the aggregate and creating internal stresses similar to those produced by the formation of ice or salt crystals, or the movement of absorbed water ahead of a freezing front. Aggregate fracture occurs when the aggregate pore structure does not allow rapid dissipation of the pore pressures and the aggregate particles are relatively weak. The amount of fracturing that results from this test has been shown to be an indicator of aggregate freeze-thaw susceptibility.

The WHFT was further developed under a research effort funded by the Michigan Department of Transportation (MDOT) and completed by Drs. Janssen and Snyder, along with Dr. Wil Hansen of the University of Michigan, in 1996 (2). The primary goal of the Michigan project was to correlate the results of the WHFT with those of the freeze-thaw test being used by MDOT at that time. This project successfully demonstrated the value of the WHFT as a rapid freeze-thaw durability screening test for many concrete coarse aggregates. However, this research also resulted in the development of recommendations for test procedure changes and equipment modifications that it was hoped would further reduce required testing efforts and might improve the reliability and interpretation of the WHFT results.

Many of the equipment and procedural modifications proposed as a result of the MDOT-sponsored study were implemented and evaluated under the study described in this report in an effort to provide Mn/DOT and other highway agencies with the best possible tool for evaluating aggregate freeze-thaw durability.

CHAPTER 2

LITERATURE REVIEW

2.1 Test Description - Original Hydraulic Fracture Test

The test begins by obtaining a sample of washed and oven-dried coarse aggregate with particle sizes ranging from 19 to 32 mm (0.75 to 1.25 in). The sample quantity must be sufficient to fill the 51-mm (2-in) deep by 254-mm (10-in) diameter test chamber (typically 2.6 - 3.0 kg [5.7 – 6.6 lb] of aggregate). The sample is submerged in a water-based silane solution for one minute to inhibit the hydrophilic tendencies of some aggregates; without this treatment, some freeze-thaw susceptible particles may become saturated during testing, which prevents the development of internal particle stresses and fracture during testing. The sample is then drained and oven-dried again. The sample is tumbled in a rock tumbler for one minute to provide uniform handling and to fracture any weakened or partially broken pieces. The sample is then screened over a 9.5-mm (0.375-in) sieve and all particles passing the sieve are discarded. Particles retained on the 9.5-mm (0.375-in) sieve become the test sample, and the number of particles and mass of the sample are recorded as the initial particle count and mass.

The sample is placed in the test chamber, and the chamber is then closed and bolted shut. The test chamber is then rotated onto its edge so that the pressure isolation/release valve is oriented vertically, and the chamber is filled with water. The water supply and release valves are secured and chamber is pressurized to 7930 kPa (1150 psi) using a nitrogen source, forcing water into the pore structure of the aggregate and compressing the air in those pores. The pressure is maintained for 5 minutes, after which the nitrogen supply valve is closed. The pressure release valve is then opened rapidly, resulting in a nearly explosive decompression of the chamber, which allows the compressed air in the aggregate pores to expand and push the water back out through the pore structure. This movement of water through the pore structure during depressurization produces internal particle stresses similar to those that develop when ice forms and water moves through the aggregate pores during freezing, and may cause some particles to fracture. The chamber is refilled with water and the process is repeated in a similar manner (with 2-minute pressurizations on subsequent pressurization cycles) for a total of 10 pressurization and release cycles, after which time the chamber is drained and the aggregate particles are removed,

oven-dried, tumbled, and sieved over 9.5-mm (0.375-in) and 4.75-mm (#4) screens. The number of particles and mass of the aggregate retained over each screen are determined, and the material retained on the 9.5-mm (0.375-in) screen is retained and subjected to an additional 10 cycles of pressurization. The process is repeated for a total of 50 cycles of pressurization.

The percentage of particles that fractured during each 10 cycles of pressurization was originally estimated as:

$$FP_i = 100(n_{4i} + n_i - n_0)/n_0 \quad (\text{Eqn. 2.1})$$

where:

FP_i = estimated percent fractures after “i” pressurization cycles,

n_{4i} = number of particles passing the 9.5-mm (0.375-in) sieve but retained on the 4.75-mm [#4] sieve after “i” pressurization cycles,

n_i = number of particles retained on the 9.5-mm (0.375-in) sieve, and

n_0 = number of particles initially tested.

The percentage of particles that fractured was then used to calculate the Hydraulic Fracture Index (HFI), which was originally defined as the number of cycles necessary to produce 10 percent fracturing. If 10 percent fracturing was achieved in 50 or fewer cycles, the HFI was originally calculated by linear interpolation as:

$$HFI = A + 10[(10 - FP_A)/(FP_B - FP_A)] \quad (\text{Eqn. 2.2})$$

where:

A = number of cycles just prior to achieving 10 percent fracturing,

FP_A = percentage of fracturing just prior to achieving 10 percent fracturing, and

FP_B = percentage of fracturing just after achieving 10 percent fracturing.

If 10 percent fracturing had not occurred by the end of 50 pressurization cycles, the HFI was originally computed as a linear extrapolation of the percent of fractures between zero and 50 cycles:

$$\text{HFI} = 50(10/\text{FP}_{50}) \quad (\text{Eqn. 2.3})$$

where:

FP_{50} = percent fracturing after 50 pressurization cycles.

Complete descriptions of the equipment, procedures and calculations associated with the Hydraulic Fracture Test, as well as information concerning the development and validation of the test, are provided in references 1 and 2.

2.2 Michigan Department of Transportation Study

2.2.1 Study Objectives and Test Program

The primary objective of this study was to determine whether the HFT could be adopted by the Michigan Department of Transportation (MDOT) as a part of their acceptance testing for concrete aggregates. Testing was performed on aggregates that span the range of materials likely to be considered for use in concrete applications, including natural and manufactured aggregates and a range of aggregate durability. Freeze-thaw tests were performed on all of the selected aggregates using MDOT test procedures, which are essentially a variation on ASTM C 666 Procedure B with careful control of the aggregate gradation and vacuum-saturation of the coarse aggregates prior to casting freeze-thaw beams. The results of these tests and additional information concerning the aggregate sources is provided in reference 2.

2.2.2 Results and Conclusions Related to Test Procedures and Analyses

Many tests were performed using different chamber pressures, chamber sizes (standard 50-mm [2-in] depth vs. 254-mm [10-in] depth), pressure release systems (manual vs. pneumatically actuated), actuator pressures and chamber linings (neoprene or none). The results of these tests led to several findings and test modifications:

- *Neoprene chamber lining.* It was found that the expansion of the pressure chamber during pressurization cycles was sufficient to allow aggregate particles to settle and reorient themselves, resulting in some crushing of the particles when the chamber contracted upon release of the pressure. This crushing of particles artificially inflated estimates of particle fractures due to the hydraulic fracture mechanism and contributed to poor correlations between HFT and freeze-thaw test results for certain aggregate types. A thin (0.8-mm [0.03-in]) neoprene pad was glued to the chamber lids to cushion the aggregate during the chamber contraction and reduce the incidence of fracture by this mechanism. Fracture rates decreased substantially (generally by more than 50 percent) with this modification.
- *Changes in HFI, particle fracture equations.* The reduction in fracture rates due to the use of the neoprene pads necessitated a change in the hydraulic fracture index. The index definition was revised to represent the number of pressurization cycles required to achieve 5 percent fracturing. Equations 2.2 and 2.3 were modified as follows:

$$HFI = A + 10[(5 - FP_A)/(FP_B - FP_A)] \quad (\text{Eqn. 2.2a})$$

$$HFI = 50(5/FP_{50}) \quad (\text{Eqn. 2.3a})$$

In addition, equation 2.1 (for estimating the number of fractured particles) was also modified (as shown in equation 2.1a below) to take into account an apparent overestimation provided in the original equation:

$$FP_i = 100(n_{4/2} + n_i - n_0)/n_0 \quad (\text{Eqn. 2.1a})$$

- *Correlations between HFI and dilation.* It was difficult to correlate the HFI with dilation measurements and durability factors obtained through freeze-thaw testing because the range of dilation measurements typically associated with good durability (0 to 0.04 percent per 100 cycles) is very compact and tied to a broad range of HFI (anything greater than 100) while the range of dilation measurements associated with marginal or poor durability (anything greater than 0.04 percent per 100 cycles) is broad and tied to a narrow range of HFI (0 to 50 for poor durability, 50 to 100 for marginal durability). In addition, the open-ended nature of

the HFI (equation 2.3a gives undefined or very large values when the percentage of fractures is zero or a very small number) makes a linear correlation difficult. For these reasons, the project researchers elected to pursue correlations between dilation and direct outputs of the HFT: particle fractures and mass loss.

- *Computation of particle fractures.* It was observed that for certain types of aggregate (e.g., sandstone, siltstone, clay ironstone and shale) an individual particle would fracture into many pieces, leading to inflated estimates of particle fractures. This problem was believed to contribute to difficulties in establishing correlations between HFT outputs and freeze-thaw test results.
- *Sample size effects.* Correlations between estimated fracture rates, computed mass loss and freeze-thaw dilations were improved when the size of the sample considered was increased (i.e., when the results of three small chamber runs were combined to produce a single test result).

Detailed descriptions of the Michigan study tests, results, analyses and conclusions are included in reference 2.

2.3 University of Minnesota Graduate School Study

2.3.1 Study Objectives and Test Program

The purpose of this project was to further refine and validate the HFT by developing new test procedures and acceptance criteria. Specific objectives included:

- Development of a correlation between mass loss and/or particle fracturing to dilation data obtained from previous freeze-thaw tests.
- Determination of appropriate acceptance/rejection criteria using the models developed above.
- Determination of the sample size required for reliable testing.

The Michigan study showed that the amount of aggregate fracturing was strongly influenced by the shape of the pressure release rate curve, which was, in turn, affected by the size, plumbing and valve operation of the test chamber. Even when seemingly identical chambers were used under identical operating conditions (chamber pressure and actuator pressure), variations in

fracture rate were observed between different apparatus. Further investigation showed that the different chambers had different apparent release rates, in spite of the use of identical operational parameters. A calibration procedure was developed to determine the combinations of chamber pressure and actuator pressure that would ensure similar pressure release rate curves; similar fracture rates were then observed for the different pieces of equipment (3).

Upon completion of the calibration process, several aggregate sources (with particle sizes in the 19 to 32 mm [0.75 to 1.25 in] range) were tested using the smaller chamber. Test and analysis procedures were similar to those developed under the SHRP program and modified under the Michigan study, except that several sieves were added to the screening operation (resulting in separate particle counts and mass measurements for materials retained on each of these sieves) and that the only particles used for subsequent pressurization cycles were those that were still in the original particle size range. This latter step helped to eliminate the overestimation of particle fracturing that occurred when a single particle would fracture repeatedly.

The sieve sizes used in this study were the 16-, 13-, 9.5- and 4.75-mm (0.625-, 0.5-, 0.375-inch and #4) sieves. The 19-mm and 25-mm (0.75-in and 1-in) sieves, which had been used in the SHRP and Michigan studies to prevent clogging of the smaller sieves, were eliminated in favor of the smaller 16-mm and 13-mm (0.625-in and 0.5-in) sieves to provide better tracking of particle size distributions after fracture and to ensure that any particle passing the top sieve did so because a fracture had taken place and not because the particle had been oriented differently during different screening operations.

2.3.2 Test Results, Analyses and Conclusions

Models were developed to correlate the data obtained from the HFT to dilation data obtained using AASHTO TP17 (T161 Procedure C). These models made use of either the cumulative particle counts or the masses retained on the different sieves, as shown below:

Hietpas Particle Count-based Dilation Model

$$\begin{aligned} \% \text{ Dilation/100 cycles} = & 3.143 - 3.135\text{E-}2 * C_{+16 \text{ mm } [+0.625 \text{ in}]} + 2.301\text{E-}2 * C_{13 - 16 \text{ mm } [0.5 - 0.625 \text{ in}]} \\ & + 2.001\text{E-}2 * C_{10 - 13 \text{ mm } [0.375 - 0.5 \text{ in}]} - 6.424\text{E-}3 * C_{5 - 10 \text{ mm } [\#4 - 0.375 \text{ in}]} \quad (\text{Eqn. 2.4}) \\ r^2 = & 0.77, n = 7 \end{aligned}$$

where:

$C_{13 - 16 \text{ mm } [0.5 - 0.625 \text{ in}]}$, $C_{10 - 13 \text{ mm } [0.375 - 0.5 \text{ in}]}$ and $C_{5 - 10 \text{ mm } [\#4 - 0.375 \text{ in}]}$ = cumulative particle counts within the indicated sieve ranges after 50 cycles of pressurization, expressed as a percentage of the initial sample particle count; and

$C_{+16 \text{ mm } [+0.625 \text{ in}]}$ = particle count on the 16-mm [0.625-in] sieve after 50 cycles of pressurization, expressed as a percentage of the initial sample particle count.

Hietpas Particle Mass-based Dilation Model

$$\begin{aligned} \% \text{ Dilation/100 cycles} = & 1.396 - 1.399\text{E-}2 * M_{+16 \text{ mm } [+0.625 \text{ in}]} - 2.861\text{E-}2 * M_{13 - 16 \text{ mm } [0.5 - 0.625 \text{ in}]} \\ & + 0.238 * M_{9.5 - 13 \text{ mm } [0.375 - 0.5 \text{ in}]} - 0.207 * M_{4.75 - 9.5 \text{ mm } [\#4 - 0.375 \text{ in}]} \quad (\text{Eqn. 2.5}) \\ r^2 = & 0.95, n = 7 \end{aligned}$$

where:

$M_{13 - 16 \text{ mm } [0.5 - 0.625 \text{ in}]}$, $M_{10 - 13 \text{ mm } [0.375 - 0.5 \text{ in}]}$ and $M_{5 - 10 \text{ mm } [\#4 - 0.375 \text{ in}]}$ = cumulative particle masses within the indicated sieve ranges after 50 cycles of pressurization, expressed as a percentage of the initial sample particle mass; and

$M_{+16 \text{ mm } [+0.625 \text{ in}]}$ = particle mass on the 16-mm [0.625-in] sieve after 50 cycles of pressurization, expressed as a percentage of the initial sample particle mass.

Figures 2.1 and 2.2 present data plots showing predicted and measured dilations using these models for the seven aggregate sources used in their development.

It was concluded that these models of freeze-thaw test dilation (for which many states already have acceptance/rejection criteria) as a function of hydraulic fracture test results (i.e., particle counts and mass measurements) offered potentially significant advantages over the use of an index value. Further refinement and validation of these models were necessary because of the small number of aggregate sources used in their development.

Figure 2.1. Predicted versus actual dilations using Hietpas' HFT count-based model (3).

Figure 2.2. Predicted versus actual dilations using Hietpas' HFT mass-based model (3).

CHAPTER 3

EXPERIMENTAL DESIGN

3.1 General Description of Test Program

The first phase and principal phase of the current research program involved the validation of the WHFT procedural modifications proposed in the recent Michigan-funded research. The principal changes center around the use of additional sieves to better characterize the nature of the fracturing that takes place during the test. Data obtained from the sieve analyses were then used to develop models for predicting freeze-thaw test dilation as a function of aggregate particle counts and masses retained on the various sieves. Additional WHFT tests were run with aggregate samples representing size fractions different from that typically tested to determine the effects of rapid freezing and thawing on aggregate particle sizes less than 19.0 mm (0.75 in).

The following aggregate size fractions were used in the test program:

- 19.0 to 37.5 mm (0.75 to 1.5 in)
- 12.5 to 19.0 mm (0.5 to 0.75 in)
- 4.75 to 12.5 mm (#4 to 0.5 in)

Twenty aggregate sources were selected to represent a range of aggregate freeze-thaw durability. Samples from each aggregate source were tested to determine fundamental properties such as absorption capacity, specific gravity and unit weight. The aggregates were then used to prepare air-entrained concrete mixtures for use in casting freeze-thaw and strength specimens and to prepare the hydraulic fracture test samples.

Freeze-thaw testing was performed on the cast beams, and the durability factor and percent dilation associated with each aggregate source was determined. These values were used in the development of models correlating rapid freezing and thawing test results to the cumulative counts and mass of particles passing designated sieve screens.

The second phase of the proposed research program involved the modification of the WHFT aggregate test chamber to accommodate larger samples of aggregate. The SHRP and Michigan

studies both indicated that a representative sample of at least 600 aggregate particles is required to reduce the variability between replicate test results to acceptable levels. The original test apparatus can hold only approximately 200 particles (sized 19 to 37.5 mm [0.75 to 1.5 in]), which means that at least three tests must be performed and combined to obtain a single test result. The use of a larger chamber would permit an entire 600-particle sample to be processed in a single test, thereby further reducing test time requirements.

3.2 Coarse Aggregate Samples

3.2.1 Size-Fraction Test Sampling

Twenty Minnesota and Iowa aggregate sources were selected to represent a broad range of aggregate freeze-thaw durability (see table 3.1); sixty-five percent of the selected aggregate sources were obtained from quarries, while the remaining thirty-five percent were from gravel pits. Aggregate samples were obtained from each source (using the ASTM D 75 procedures) in quantities sufficient for all the proposed characterization tests, WHFT and freeze-thaw durability testing. The samples were screened into the previously described particle size fractions (i.e., 4.75 to 12.5 mm, 12.5 to 19.0 mm, 19.0 to 37.5 mm [#4 to 0.5 in, 0.5 to 0.75 in, and 0.75 to 1.5 in]) until sufficient quantities of each size fraction had been obtained.

Each aggregate source size fraction was thoroughly remixed to ensure uniformity of the material, since the original samples were sometimes obtained from more than one stockpile, each containing the same source aggregate but with varying top sizes. Samples were obtained from each aggregate source size fraction for performing the following tests:

- specific gravity and absorption capacity testing (ASTM C 127 “Specific Gravity and Absorption of Coarse Aggregate”),
- magnesium sulfate testing (ASTM C 88 “Standard Test Method for Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate”),
- hydraulic fracture testing, and
- for determining the percentage of carbonates present.

Table 3.1. Summary of aggregate sources, locations and expected durabilities.

			Location			
Aggregate Source	Mn/DOT Pit Designation	Expected Durability	County/State	SEC	TWN	RNG
QUARRIED						
Aaland, Zumbrota	25083	Fair	Goodhue, MN	34	110	15
Big Springs, Harmony	23096	Good	Fillmore, MN	09	101	10
Bryan Rock, Shakopee	70006	Poor	Scott, MN	29	115	23
Coralville Concrete Ledge, Waterloo	N/A	Poor	Waterloo, IA			
Early Chapel	155011	Poor	Early Chapel, IA			
Edward Kramer & Sons, Burnsville	19106	Good	Dakota, MN	33	027	24
Goldberg, Rochester	55037	Good	Olmsted, MN	36	108	14
Michigan Limestone, Cedarville Plant	197001	Good	Mackinac, MI			
Osmundson, Grand Meadow	50011	Fair	Mower, MN	09	103	14
Shiely Grey Cloud (Larson)	182002	Good	Washington, MN	26	27	22
Southern MN Corp. (SMC) Mankato	74071	Poor	Steele, MN	33	108	20
Swedberg	66084	Poor	Rice County, MN	04	109	20
Ulland Northwood, Iowa	193018	Good	Worth, IA	10	99	22
GRAVEL						
Ashwill, Kingston	47076	Uncertain	Meeker, MN	34	120	29
Johnson, Henderson	72001	Good	Sibley, MN	26	113	26
Johnson Le Sueur	140002	Poor	Le Sueur, MN	15	111	26
Loeffler, Halma	35002	Good	Kittson, MN	17	160	46
Mark, Underwood	56003	Good	Otter Tail, MN	10	132	41
Northern Con, Luverne	67001	Good – Poor	Rock, MN	06	102	44
North Star Kasota	140001	Poor	Le Sueur, MN	04	109	26

3.2.2 As-Produced Material

In addition to the sampling/testing of each *size fraction*, an “*as-produced*” materials blend was prepared for use in producing air-entrained concrete mixtures from which freeze-thaw and strength specimens were cast. These “as-produced” blends comprised 50 percent material retained on the 19 mm (0.75 in) sieve, and 50 percent passing the same sieve, a blend commonly used in Minnesota PCC paving mixtures. This blend was accomplished as follows:

- 50 percent 19.0 to 37.5 mm (0.75 to 1.5 in) material
- 25 percent 12.5 to 19.0 mm (0.5 to 0.75 in) material
- 25 percent 4.75 to 12.5 mm (#4 to 0.5 in) material

Further sieve analyses were not performed on the blended materials. The specified blend was not achieved for two of the aggregate sources (Ashwill, Kingston and Waterloo, Iowa), as described below.

Ashwill, Kingston

The CA60 gradation band was used in the development of the as-produced aggregate proportions for this source, which was deficient in aggregate particles larger than 19.0 mm (0.75 in). The following proportions were used for Ashwill, Kingston:

- 37.5 percent 12.5 to 19.0 mm (0.5 to 0.75 in) material
- 62.5 percent 4.75 to 12.5 mm (#4 to 0.5 in) material

Waterloo, Iowa

Aggregate from this source was available from a previous durability study performed in 1998. For the 1998 study, the aggregate was sieved into component size fractions and re-blended to meet the middle of the AASHTO M43 specification Grade 467 (37.5-mm [1.5-in] top size).

Therefore, the proportions of the as-produced material from this source were as follows:

- 50 percent 19.0 to 37.5 mm (0.75 to 1.5 in) material
- 20 percent 12.5 to 19.0 mm (0.5 to 0.75 in) material
- 27.5 percent 4.75 to 12.5 mm (#4 to 0.5 in) material
- 2.5 percent minus #4 material

It should be noted that the tests performed on cast PCC specimens using this aggregate source under the 1998 study were identical to some of the tests that would have been performed under the current study; where possible, the 1998 test results were used and the tests were not repeated in the current study. These tests are described in more detail in section 3.4 of this report.

3.2.3 As-Produced Test Sampling

Samples were split from the newly developed “as-produced material” and prepared for use in air-entrained PCC mixtures and for use in determining the following fundamental aggregate properties:

- ASTM C 127 “Specific Gravity and Absorption of Coarse Aggregate”
- ASTM C 29 “Unit Weight and Voids in Aggregate”
- ASTM C 136 “Sieve Analysis of Fine and Coarse Aggregates”

3.3 PCC Mix Design

A standard air-entrained PCC paving mixture was prepared for each of the 20 selected aggregates sources; Mn/DOT Mix 3A41 (meeting the requirements of specification 2461) was used as the base mix design. The mixtures consisted of natural river sand, Type I cement, water and an air-entraining admixture. The air-entraining admixture was used to ensure that any freeze-thaw durability problems observed were due to the coarse aggregate and not the cement mortar matrix. The coarse aggregate was conditioned to be in a saturated, surface-dry (SSD) condition at the time of batching to guarantee critical saturation when subjected to rapid freezing and thawing; the fine aggregate was oven-dry at the time of batching. A water-cement ratio of 0.40, the maximum currently allowed in Minnesota PCC paving mixtures, was used for most of the PCC mixtures prepared under this study. Table B-1 (see appendix B) summarizes the batch weights used to prepare each PCC mixture.

The plastic air content was measured with the Press-R-Meter in accordance with ASTM C 231 “Air Content of Freshly Mixed Concrete by the Pressure Method,” and the slump was measured using a standard slump cone in accordance with ASTM C 143 “Slump of Hydraulic Cement

Concrete.” Table B-1 (see appendix B) summarizes the plastic air content and slump measurements for each mixture.

3.4 Test Specimens

Six beam test specimens measuring 75 mm × 100 mm × 400 mm (3 in × 4 in × 16 in) and three cylindrical specimens measuring 152 mm diameter × 305 mm (6 in × 12 in) were cast from each mixture for freeze-thaw and strength testing (14-day compression and 14-day static modulus of elasticity), respectively. The compressive strength tests and static modulus of elasticity testing were performed in accordance with ASTM C 39 “Compressive Strength of Cylindrical Specimens” and ASTM C 469 “Static Modulus of Elasticity and Poisson’s Ratio of Concrete in Compression,” respectively. A slice was taken from one freeze-thaw beam of each mixture and prepared for linear traverse analysis (ASTM C 457 “Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete”) to verify that an adequate air void system was present, thereby ensuring that any freeze-thaw durability problems observed could be attributed solely to the use of a non-durable aggregate rather than unsound mortar.

The freeze-thaw beams were cured in a lime-saturated water bath for 14 days, after which time they were subjected to rapid freezing and thawing in accordance with AASHTO TP17 (T161 Procedure C). The freeze-thaw durability of these mixtures was evaluated using the relative dynamic modulus (calculated according to ASTM C 215 “Fundamental Transverse, Longitudinal, and Torsional Resonant Frequencies of Concrete Specimens”) and dilation criteria.

3.5 Hydraulic Fracture Testing – Small Chamber

3.5.1 Small Chamber Test Samples

Five samples of oven-dry coarse aggregate sufficient to fill the test chamber (approximately 2.6 to 3.0 kg [5.6 to 6.6 lb] of aggregate) were made from each source for each of the three previously defined size fractions. Thus, a total of approximately 300 hydraulic fracture test samples were prepared for the small chamber (five samples representing each of three size fractions for each of 20 sources). Some sources did not contain enough material larger than 19 mm (0.75 in) to prepare five replicate specimens (as indicated in table 3.2), so the actual total number of test samples prepared was somewhat less than 300.

Testing of the samples was performed randomly within blocks of replicates (i.e., one replicate specimen of each source within a particular size fraction was tested in random order before the next block of replicates was tested, also in random order). This was done to minimize the potential effects of both random and systematic bias due to the effects of any extraneous factors that may have been present (e.g., operator procedural differences, uncontrolled and unforeseen changes in the test equipment, etc.).

A few specimens were either untested (due to time and funding constraints) or were spoiled (as a result of occasional handling or testing errors). Table 3.2 presents a summary of which tests were completed with respect to initial size fraction, aggregate source and replicate number. Table cells labeled N/A (not available) indicate that the original source material was deficient in 19.0 mm (0.75 in) plus material, thereby preventing the preparation of the replicate sample. A total of 272 specimens did yield usable results after testing, including no fewer than three replicates for each source-size fraction for which material was available.

3.5.2 Modified Test Procedure

The original hydraulic fracture test procedure (as briefly described previously in section 2.1) was modified slightly to account for the additional size fractions included in the experimental design. The following is a brief description of the test procedure followed during this study; the complete modified procedure is presented in appendix A.

The test begins by obtaining an appropriately sized sample of oven-dry coarse aggregate that is sufficient to fill the 51-mm (2-in) deep by 254-mm (10-in) diameter test chamber. This typically requires 2.6 to 3.0 kg (5.7 to 6.6 lb) of aggregate. The sample is submerged in a water-based silane solution (Hydrozo Enviroseal 40 was used for this study) for one minute to inhibit the hydrophilic tendencies of some aggregates, which may reduce the effectiveness of the test. The sample is then drained and oven-dried again. The sample is tumbled in a rock tumbler for one minute to provide uniform handling and to fracture any weakened or partially broken pieces.

Table 3.2. Small chamber hydraulic fracture test matrix.

Aggregate Source	Completed Hydraulic Fracture Testing (as denoted by a “X”)														
	Initial Size Fraction														
	4.75 to 12.5 mm (#4 to 0.5 in)					12.5 to 19.0 mm (0.5 to 0.75 in)					19.0 to 37.5 mm (0.75 to 1.5 in)				
	Replicate Number														
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Ashwill	X	X		X	X	X	X	X	X	X	N/A	N/A	N/A	N/A	N/A
Big Springs, Harmony	X	X	X			X	X	X	X	X	X	X	X	X	X
Bryan Rock, Shakopee	X	X	X	X		X	X	X	X	X	X	X	X	X	X
Cedarville Plant, Michigan	X	X		X		X	X	X	X	X	X	X	X	X	
Early Chapel	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Edward Kramer & Sons, Burnsville	X	X		X	X	X	X	X	X		X	X	X	X	X
Goldberg, Rochester	X	X	X	X		X		X	X	X	X	X	X	X	X
Grandmeadow, Osmundson	X	X	X	X		X	X	X	X	X	X	X	X	X	X
Halma, Loeffler Sand & Gravel	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Johnson Henderson	X	X		X	X	X	X	X	X	X	X	X	X	X	X
Johnson, Le Sueur	X	X		X	X	X	X	X	X	X	X	X	X	X	X
Mark, Underwood	X	X	X	X		X	X	X	X	X	X	X	X	X	X
North Star Kasota	X	X		X	X	X	X	X	X	X	X	X	X	X	X
Northern Con, Luverne	X	X		X		X	X	X	X	X	X	X	X	X	X
Shiely Grey Cloud (Larson)	X	X	X	X		X	X	X	X	X	X	X	X	X	X
SMC Mankato	X	X		X	X	X	X	X		X	X	X	X	X	X
Swedberg	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Ulland Northwood, Iowa	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Waterloo, Coralville Concrete Ledge	X	X	X	X	X	X	X	X	X	X	X	N/A	X	X	N/A
Zumbrota, Aaland	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

N/A: Source deficient in 19 mm plus material.

■: Sample prepared, however, testing not completed due to time constraints or errors.

Table 3.3. Screens used in preparing HFT test samples for various initial size fractions.

Sieve Size	Initial Size Fraction		
	4.75 mm to 12.5 mm (#4 to 0.5 in)	12.5 mm to 19.0 mm (0.5 in to 0.75 in)	19.0 mm to 37.5 mm (0.75 in to 1.5 in)
<i>No. of Sub-Samples</i>	5	4	3
37.5 mm (1.5 in)			X – Material Excluded
25.0 mm (1 in)			X
19.0 mm (0.75 in)		X – Material Excluded	X
16.0 mm (0.625 in)		X	X
12.5 mm (0.5 in)	X – Material Excluded	X	
9.50 mm (0.375 in)	X	X	
8.00 mm (0.3125 in)	X		
6.35 mm (0.25 in)	X		
4.75 mm (#4)	X		
Pan	X – Material Excluded	X – Material Excluded	X – Material Excluded

The sample is then split into small sub-samples which are screened over the appropriate sieve sizes, as indicated (by “X”) in table 3.3. The smaller sub-samples are required to prevent overloading of the sieves by the aggregate. The material retained on the largest screen size used and on the pan is excluded from the sample for all three cases, as shown in table 3.3. For example, if the size fraction 19.0 to 37.5 mm (0.75 to 1.5 in) was the target particle range, the material would need to be screened over the 37.5-mm (1.5-in), 25.0-mm (1-in), 19.0-mm (0.75-in) and 16.0-mm (0.625-in) sieves and over the pan. The particles retained on the 37.5-mm (1.5-in) sieve and on the pan would be excluded from the sample, since these particle sizes do not fall within the target particle range. The material retained on the next sieve size smaller than the target particle range (in this example, the 16.0-mm [0.625-in] sieve) is included in the sample. This material is included in the target particle range to account for the particles which may or may not be retained on the 19.0 mm screen in future screenings due to reorientation of the particles.

The mass and number of particles retained on the remaining screens are determined (except for the 4.75 to 12.5 mm (#4 to 0.5 in) size range, for which only the particle masses are determined due to the extremely large number of particles that make up this sample). The sample is then placed into the test chamber, which is closed and bolted shut.

The test chamber is then rotated onto its edge so that the pressure isolation/release valve is oriented vertically, and the chamber is filled with water. The water supply and release valves are

secured and chamber is pressurized to 7930 kPa (1150 psi) using a nitrogen source, forcing water into the pore structure of the aggregate and compressing the air in those pores. The pressure is maintained for 5 minutes, after which the nitrogen supply valve is closed. The pressure release valve is then opened rapidly, resulting in a nearly explosive decompression of the chamber, which allows the compressed air in the aggregate pores to expand and push the water back out through the pore structure. This movement of water through the pore structure during depressurization produces internal particle stresses similar to those that develop when ice forms and water moves through the aggregate pores during freezing, and may cause some particles to fracture. The chamber is refilled with water and the process is repeated in a similar manner (with 2-minute pressurizations on subsequent pressurization cycles) for a total of 10 pressurization and release cycles, after which time the chamber is drained and the aggregate particles are removed, oven-dried, tumbled, and sieved over 9.5-mm (0.375-in) and 4.75-mm (#4) screens. The number of particles and mass of the aggregate retained over the screens are listed in table 3.4. The mass and number of particles retained over each screen is determined, and the material that is retained on the 4.75-mm and larger sieves is retained and subjected to an additional 10 cycles of pressurization. The process is repeated for a total of 50 cycles of pressurization.

Table 3.4. Screens used in testing HFT samples for various initial size fractions.

Sieve Size	Initial Size Fraction		
	4.75 to 12.5 mm (#4 to 0.5 in)	12.5 to 19.0 mm (0.5 to 0.75 in)	19.0 to 37.5 mm (0.75 to 1.5 in)
37.5 mm (1.5 in)			
25.0 mm (1 in)			X
19.0 mm (0.75 in)			X
16.0 mm (0.625 in)		X	X
12.5 mm (0.5 in)		X	X
9.50 mm (0.375 in)	X	X	X
8.00 mm (0.3125 in)	X	X	X
6.35 mm (0.25 in)	X	X	X
4.75 mm (#4)	X	X	X
Pan	X	X	X

3.5.3 Normalization of Hydraulic Fracture Results

The hydraulic fracture data was normalized to account for variations in particle counts and mass retained between individual samples due to the differences in particle size and shape. Each

sample was normalized by comparing the number or mass of particles retained on each sieve after 50 cycles to the total number or mass of particles contained in the initial size fraction at 0 pressurization cycles. The percent of particles and mass retained for each *sample* was calculated as defined below:

Percentage of Original Particles Retained (POPR) =

$$100 \times \frac{\text{Number of particles on sieve } I \text{ (after 50 cycles)}}{\text{Total number of particles in sample at 0 cycles}} \quad (\text{Eqn. 3.1})$$

Percentage of Original Mass Retained (POMR) =

$$100 \times \frac{\text{Mass retained on sieve } I \text{ (after 50 cycles)}}{\text{Total mass of sample at 0 cycles}} \quad (\text{Eqn. 3.2})$$

where: I = pan, 4.75-mm (#4), 8.00-mm (0.3125-in), 9.50-mm (0.375-in), 12.5-mm (0.5-in), 16.0-mm (0.625-in), 19.0-mm (0.75-in), 25.0-mm (1-in), or 37.5-mm (1.5-in) sieve

The average percentage of particles and mass retained for each *source* was also calculated by combining all the replicates of each source together into one sample as defined below:

Average Percentage of Original Particles Retained (APOPR) =

$$100 \times \frac{\sum_{k=1}^n \text{Number of particles on sieve } I \text{ (after 50 cycles)}}{\sum_{k=1}^n \text{Total number of particles in sample at 0 cycles}} \quad (\text{Eqn. 3.3})$$

Average Percentage of Original Mass Retained (APOMR) =

$$100 \times \frac{\sum_{k=1}^n \text{Mass retained on sieve } I \text{ (after 50 cycles)}}{\sum_{k=1}^n \text{Total mass of sample at 0 cycles}} \quad (\text{Eqn. 3.4})$$

where: I = pan, 4.75-mm (#4), 8.00-mm (0.3125-in), 9.50-mm (0.375-in), 12.5-mm (0.5-in),
16.0-mm (0.625-in), 19.0-mm (0.75-in), 25.0-mm (1-in), or 37.5-mm (1.5-in) sieve
 k = replicate number
 n = total number of replicates

3.6 Hydraulic Fracture Testing – Large Chamber

3.6.1 Large Chamber Test Samples

Three samples of oven-dry coarse aggregate sufficient to fill the large test chamber (approximately 15 kg [33 lb] of aggregate) were prepared with the 19.0 to 37.5 mm (0.75 to 1.5 in) size fraction of the following four sources, which represent a range of freeze-thaw resistance: Johnson Henderson (Gravel), North Star Kasota (Gravel), Edward Kramer and Sons (Quarried Carbonate) and Early Chapel (Quarried Carbonate). As described previously for the small chamber, the order of testing the individual replicates was determined randomly to minimize the effects of random and systematic bias due to the effects of possible extraneous factors.

3.6.2 Test Procedure

The general test procedure followed when using the large hydraulic fracture chamber is the same as that discussed for small chamber use (see section 3.5.2) and described in Appendix A. The only difference is that replicate tests are not required because the large chamber holds enough aggregate particles to accurately characterize the D-cracking potential of a coarse aggregate source with a single test sample.

3.6.3 Normalization of Hydraulic Fracture Test Results

The large chamber hydraulic fracture data were interpreted in the same manner as described for the small chamber data (see section 3.5.3).

CHAPTER 4

TEST RESULTS AND ANALYSES

4.1 Concrete Properties

Microscopical analyses of the concrete air void systems were performed on one polished concrete slice taken from a selected strength specimen for each mixture to verify that any durability failures were due to the coarse aggregate and not to the cement mortar matrix. Table 4.1 presents a summary of the air void characteristics measured for each concrete mixture. Most authorities (4, 5, 6) recommend a spacing factor of 0.2 mm (0.008 in) or less and a specific surface equal to or exceeding $27 \text{ mm}^2/\text{mm}^3$ ($600 \text{ in}^2/\text{in}^3$) for concrete intended to be resistant against repeated cycles of freezing and thawing. All mixtures but one met the specific surface criterion, and the spacing factor criterion was met for 15 of the 20 mixtures. The five mixtures that exceeded the spacing factor criterion did so by 10 percent or less (as indicated in italics in table 4.1). No mixture failed both the specific surface and spacing factor criteria.

Table 4.2 presents the average durability factors and dilation measures for each PCC mixture. Neville reported that durability factors greater than 60 indicate satisfactory freeze-thaw durability, durability factors between 40 and 60 indicate doubtful freeze-thaw performance, and durability factors less than 40 indicate unsatisfactory durability (7). Mn/DOT considers durability factors greater than 80 as satisfactory, durability factors between 40 and 80 as fair, and durability factors less than 40 as unsatisfactory. The Mn/DOT criteria reflect an expected concrete pavement design life of 35 years. Dilations exceeding 0.04 percent per 100 cycles are also generally considered to indicate nondurable concrete.

Using the durability factors categories adopted by Mn/DOT, the aggregate sources would be categorized as follows (in order of descending durability factor, with the measured durability factor given in brackets for each aggregate source):

“Satisfactory” Freeze-Thaw Resistance ($DF > 80$)

- Michigan Limestone, Cedarville Plant (Quarried) [99.3]
- Shiely Grey Cloud (Larson [Quarried]) [98.8]

Table 4.1. Summary of air void system measurements.

Source	Batch No.	Plastic Air Content (%)	Hardened Air Content (%)	Spacing Factor (mm)	Specific Surface (mm ² /mm ³)
QUARRIED					
Aaland, Zumbrota*	1	6.4	5.26	0.1499	34.8
Big Springs, Harmony	1	3.5	3.37	0.1448	40.7
Bryan Rock, Shakopee*	1	3.5	3.32	0.2210	27.4
Coralville Concrete Ledge, Waterloo*	1	7.4	7.1	0.1220	37.2
	5	4.7	5.1	0.2000	24.1
	7	5.2	4.8	0.1630	31.5
Early Chapel*	1	3.6	3.77	0.2057	27.5
Edward Kramer & Sons, Burnsville	1	4.9	3.34	0.1753	34.3
Goldberg, Rochester	1	4.4	2.7	0.1880	34.8
Osmundson, Grand Meadow*	2	5.0	4.52	0.1880	28.6
Michigan Limestone, Cedarville Plant	1	5.9	4.2	0.1270	43.1
Shiely Grey Cloud (Larson)	1	5.3	3.25	0.2108	29.3
SMC Mankato	1	4.8	3.66	0.1905	30.5
Swedberg	1	3.5	2.74	0.1753	36.9
Ulland Northwood, Iowa	1	3.5	1.6	0.2134	39.0
GRAVEL					
Ashwill, Kingston	1	4.9	4.16	0.1372	40.0
Johnson, Henderson	1	4.4	3.3	0.2210	27.2
Johnson Le Sueur	1	5.7	4.9	0.1651	31.4
Loeffler, Halma	1	5.9	4.9	0.1092	47.4
Mark, Underwood	1	6.4	5.6	0.1524	32.1
Northern Con, Luverne	1	7	3.2	0.1397	45.9
North Star Kasota	1	4.5	2.5	0.1981	34.4

* Linear traverse analysis performed by different operator than subsequent tests.

- Ashwill, Kingston (Gravel) [97.1]
- Ulland Northwood, Iowa (Quarried) [97.0]
- Mark, Underwood (Gravel) [95.5]
- Goldberg, Rochester (Quarried) [95.2]
- Loeffler, Halma (Gravel) [93.9]
- Johnson, Henderson (Gravel) [90.2]
- Johnson, Le Sueur (Gravel) [88.3]
- Northern Con, Luverne (Gravel) [83.8]
- Aaland, Zumbrota (Quarried) [80.5]

“Fair” Freeze-Thaw Resistance (DF = 40 to 80)

- North Star Kasota (Gravel) [79.4]
- Edward Kramer and Sons, Burnsville (Quarried) [78.6]
- Osmundson, Grand Meadow (Quarried) [78.4]

“Unsatisfactory” Freeze-Thaw Resistance (DF < 40)

- Early Chapel, Iowa (Quarried) [36.1]
- Coralville Concrete Ledge, Waterloo (Quarried) [31.2]
- Swedberg (Quarried) [26.2]
- Big Springs, Harmony (Quarried) [18.0]
- Bryan Rock, Shakopee (Quarried) [16.0]
- SMC Mankato (Quarried) [13.4]

All of the mixtures exhibiting unsatisfactory durability factors also had excessive average dilations.

Specimens exhibiting unsatisfactory freeze-thaw resistance and containing marginal air void systems were visually inspected using a stereomicroscope to verify that the majority of deterioration was contained within the aggregate particles. Therefore, microscopic examinations were performed on slices taken from freeze-thaw damaged concrete specimens comprising “Bryan Rock, Shakopee” and “Early Chapel, Iowa” aggregates; physical inspection was not

performed on concrete specimens comprising “Ulland, Northwood”, “Shiely Grey Cloud (Larson)”, or “Johnson, Henderson” due to the high durability factors and low dilation measurements obtained for these specimens. Severe microcracking could be seen in the aggregate particles and not in the cement matrices of the freeze-thaw damaged concrete specimens with marginal spacing factors. Therefore, it can be concluded that all of the PCC mixtures exhibiting low durability factors did so because they contained deleterious aggregate materials and not because the cement matrix was nondurable.

The average strength measured for each PCC mixture is also presented in table 4.2 (see table B-2 for measured strength results of each PCC specimen). All strength test results are well within the range generally considered necessary for durable concrete (i.e., $f_c > 27.6$ MPa [4000 psi]).

4.2 Specific Gravity and Absorption Capacity

The specific gravity and absorption capacity were determined for the “as-produced” materials and each size fraction of each source (i.e., 4.75 to 12.5 mm, 12.5 to 19.0 mm, 19.0 to 37.5 mm [#4 to 0.5 in, 0.5 to 0.75 in, 0.75 to 1.5 in]) in accordance with ASTM C 127 “Specific Gravity and Absorption of Coarse Aggregate.” Table 4.3 summarizes the results of these tests.

Mn/DOT considers quarried carbonates with measured absorption capacity values greater than 1.7 percent to have potential for durability problems and, therefore, does not allow the use of such sources in concrete paving applications. According to Mn/DOT specifications, the following aggregate sources would be considered unsatisfactory for use in paving applications based on the absorption capacity values measured for the as-produced material (as shown in brackets for each aggregate source):

- SMC Mankato [4.437 %]
- Osmundson, Grand Meadow [3.781 %]
- Aaland, Zumbrota [3.242 %]
- Edward Kramer & Sons, Burnsville [3.150 %]
- Shiely Grey Cloud (Larson) [2.972 %]
- Bryan Rock, Shakopee [2.928 %]

Table 4.2. Summary of strength and durability test data.

Source	Avg. Compressive Strength ¹ (MPa)	Avg. Static E ¹ (GPa)	Avg. DF	Avg. Dilation ² (%)	Avg. Dilation / 100 Cycles (%)
QUARRIED					
Aaland, Zumbrota	31.2		80.5	0.029	0.011
Big Springs, Harmony	40.7	31.4	18.0	0.044	0.050
Bryan Rock, Shakopee	47.3		16.0	0.089	0.118
Coralville Concrete Ledge, Waterloo ²	41.6	30.0	31.2	0.099	0.073
Early Chapel	45.2		36.1	0.089	0.050
Edward Kramer & Sons, Burnsville	30.1	21.6	78.6	0.053	0.018
Goldberg, Rochester	42.8	27.6	95.2	0.012	0.004
Michigan Limestone, Cedarville Plant	34.3	30.9	99.3	0.002	0.001
Osmundson, Grand Meadow	48.4		78.4	0.055	0.018
Shiely Grey Cloud (Larson)	44.0	27.0	98.8	0.011	0.004
SMC Mankato	36.5	24.2	13.4	0.068	0.111
Swedberg	32.8	28.2	26.2	0.101	0.078
Ulland Northwood, Iowa	40.9	34.6	97.0	-0.008	-0.003
GRAVEL					
Ashwill, Kingston	38.4	30.7	97.1	0.010	0.003
Johnson, Henderson	35.5	29.0	90.2	0.016	0.005
Johnson Le Sueur	30.3	28.8	88.3	0.023	0.008
Loeffler, Halma	34.5	30.4	93.9	0.018	0.006
Mark, Underwood	30.2	29.8	95.5	0.012	0.004
Northern Con, Luverne	30.9	23.8	83.8	0.024	0.008
North Star Kasota	34.7	30.1	79.4	0.032	0.011

¹ Modulus of elasticity and compression tests were performed after 28 days of curing.

² Percent dilation is at failure (when the relative dynamic modulus reaches 60 percent) or 300 cycles, whichever came first.

Table 4.3. Summary of specific gravity and absorption capacity test results.

Source	Specific Gravity (at 23 °C)				Absorption Capacity (%)			
		Size Fraction (mm)				Size Fraction (mm)		
	As- Produced	4.75 - 12.5	12.5 - 19.0	19.0 - 37.5	As- Produced	4.75 - 12.5	12.5 - 19.0	19.0 - 37.5
QUARRIED								
Aaland, Zumbrota	2.503	2.450	2.511	2.530	3.242	4.310	3.193	2.817
Big Springs, Harmony	2.551	2.406	N/A	2.626	1.845	3.776	N/A	1.043
Bryan Rock, Shakopee	2.497	2.508	2.489	2.560	2.928	3.233	2.733	2.610
Coralville PCC Ledge, Waterloo	2.564	2.542	2.55	N/A	2.620	2.431	2.125	N/A
Early Chapel	2.481	2.423	2.477	2.489	2.724	2.928	2.673	2.530
Edward Kramer & Sons, Burnsville	2.547	2.461	2.542	N/A	3.150	4.791	3.196	N/A
Goldberg, Rochester	2.586	2.528	2.558	2.643	2.572	2.870	2.089	1.464
Michigan LS, Cedarville Plant	2.764	2.773	2.765	2.774	0.454	0.633	0.483	0.355
Osmundson, Grand Meadow	2.413	2.447	N/A	2.382	3.781	4.130	N/A	3.291
Shiely Grey Cloud (Larson)	2.427	2.456	2.478	2.475	2.972	3.606	2.792	2.501
SMC Mankato	2.445	2.430	2.435	N/A	4.437	5.031	4.201	N/A
Swedberg	2.527	2.464	2.565	2.610	2.843	3.833	2.136	1.653
Ulland Northwood, Iowa	2.736	2.606	2.721	2.669	0.950	1.520	0.884	0.707
GRAVEL								
Ashwill, Kingston	2.635	2.642	2.629	N/A	1.697	1.622	0.959	N/A
Johnson, Henderson	2.653	2.605	N/A	2.657	1.131	1.460	N/A	0.987
Johnson Le Sueur	2.639	2.631	2.652	2.636	1.443	1.586	1.246	1.263
Loeffler, Halma	2.649	2.611	2.616	2.627	1.038	1.426	1.057	0.844
Mark, Underwood	2.719	2.641	2.653	2.65	0.785	1.123	0.827	0.704
Northern Con, Luverne	2.611	N/A	N/A	N/A	1.386	N/A	N/A	N/A
North Star Kasota	2.655	N/A	N/A	2.654	1.129	N/A	N/A	0.951

- Swedberg [2.843 %]
- Early Chapel [2.724 %]
- Coralville PCC Ledge, Waterloo [2.620 %]
- Goldberg, Rochester [2.572 %]
- Big Springs, Harmony [1.845 %]

Figure 4.1 presents a plot of durability factor results versus the measured absorption capacities for the as-produced quarried carbonate materials used in the PCC mixtures. Mn/DOT's accepted boundaries for satisfactory, fair and unsatisfactory freeze-thaw durability are shown, along with the 1.7 percent absorption capacity line.

Figure 4.1. Durability factor versus coarse aggregate absorption (carbonate sources only).

In general, it appears that the Mn/DOT acceptance limit for absorption capacity successfully eliminates all aggregate sources with unsatisfactory or fair freeze-thaw resistance (durability factor < 80). However, the absorption capacity criterion also eliminates three sources (Goldberg – Rochester, Shiely Grey Cloud [Larson] and Aaland, Zumbrota) with satisfactory freeze-thaw resistance (durability factor greater than 80) and two other sources (Kramer and Sons, and Osmundson, Grand Meadow) that would probably provide satisfactory freeze-thaw resistance as well (durability factors very close to 80).

4.3 Magnesium Sulfate Test

Aggregate samples of each coarse aggregate source were brought to the Mn/DOT Research Laboratory for magnesium sulfate testing in accordance with ASTM C 88 “Standard Test Method for Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate.” The material was split into the following size fractions: 4.75 to 9.50 mm (#4 to 0.375 in), 9.50 to 12.5 mm (0.375 to 0.5 in), 12.5 to 19.0 mm (0.5 to 0.75 in), 19.0 to 25.0 mm (0.75 to 1.0 in), and

25.0 to 37.5 mm (1.0 to 1.5 in). Table 4.4 presents the percent mass loss due to magnesium sulfate testing for each aggregate sample (by source and size fraction).

According to ASTM C 33 “Standard Specification for Concrete Aggregates,” the maximum allowable percent loss from the magnesium sulfate soundness test (at 5 cycles) is 18 percent in severe freeze-thaw locations. Mn/DOT specifies that coarse aggregate (by weight) used in concrete mixtures shall not exceed 15 percent loss at 5 cycles for any fraction (8). Shaded cells in table 4.4 indicate source/size fraction combinations that would not be allowed for use as coarse aggregate in PCC mix applications.

Table 4.4. Magnesium sulfate test results.

Coarse Aggregate Source	Percent Mass Loss				
	Size Fraction (mm)				
	4.75 to 9.50	9.50 to 12.5	12.5 to 19.0	19.0 to 25.0	25.0 to 37.5
QUARRIED					
Aaland, Zumbrota	36.18	32.39	17.34	18.51	5.95
Big Springs, Harmony	N/A	N/A	13.05	7.03	5.14
Bryan Rock, Shakopee	4.33	3.11	3.03	1.6	1.22
Coralville Concrete Ledge, Waterloo	8.65	11.31	6.91	N/A	N/A
Early Chapel	15.83	14.64	12.42	3.17	N/A
Edward Kramer & Sons, Burnsville	28.75	22.65	18.76	15.59	N/A
Goldberg, Rochester	18.8	11.28	10.66	4.56	8.43
Michigan Limestone, Cedarville Plant	1.23	1.42	0.3	1.41	0.54
Osmundson, Grand Meadow	11.97	11.05	5.61	2.06	3.65
Shiely Grey Cloud (Larson)	13.73	12.73	4.3	5.23	1.7
SMC Mankato	55.51	66.18	39.71	36.34	38.21
Swedberg	28.4	28.39	18.36	15.3	4.77
Ulland Northwood, Iowa	5.86	4.73	1.64	2.35	1.94
GRAVEL					
Ashwill, Kingston	3.79	4.76	2.21	N/A	N/A
Johnson, Henderson	6.56	11.15	3.57	6.23	7.57
Johnson Le Sueur	8.46	9.36	5.38	7.25	4.97
Loeffler, Halma	2.93	4.44	1.52	1.04	N/A
Mark, Underwood	2.53	4.24	3.87	6.56	0.4
Northern Con, Luverne	14.4	16.58	10.7	14.51	1.84
North Star Kasota	6.99	5.75	2.12	5.22	0.91

Note: Shaded areas indicate test results that fail Mn/DOT acceptance criterion for concrete aggregate.

These results are based on tests of aggregate samples collected in 1998 and the size fractions available for soundness testing. Some aggregate sources were deficient in material with particle sizes larger than 19.0 mm (0.75 in), so these larger particle sizes were not always tested, as shown in table 4.4.

In general, it appears that the percent mass loss increases with decreasing particle size for most of the aggregate sources tested. While the reason for this trend is not known with certainty, the following hypotheses are offered:

- (1) the weaker aggregate particles are typically broken down into smaller particles during production processing, resulting in numbers of weaker particles (possibly more susceptible to magnesium sulfate testing) in the smaller size fractions;
- (2) it takes less internal expansive stress (due to salt crystallization) in smaller particles to produce fracturing than in larger size particles;
- (3) smaller particles have a greater surface area per unit volume of material than do larger particles, thereby allowing a greater amount of solution to penetrate and form a greater volume of salt crystals; and/or
- (4) a given amount of degradation per unit surface area will result in higher percentages of mass loss for a given sample mass as the average particle size decreases (and surface area increases).

4.3.1 Correlation with Rapid Freezing and Thawing Test Results

Figure 4.2 presents a plot of the freeze-thaw test results (durability factor) versus the results of magnesium sulfate testing (mass loss) for each aggregate source and size fraction. This figure also includes Mn/DOT's accepted boundaries for defining satisfactory, fair and unsatisfactory freeze-thaw durability, as well as the acceptance-rejection boundary for magnesium sulfate testing mass loss (i.e., 15 percent). In considering this graph, it is important to remember that freeze-thaw test beams comprised coarse aggregate representing all of the relevant particle size fractions (50 percent 19 to 38 mm [0.75 to 1.5 in], 25 percent 12.5 to 19 mm [0.5 to 0.75 in] and 25 percent 4.75 to 12.5 mm [#4 to 0.5 in] material), as described previously.

Figure 4.2. Durability factor versus mass loss from magnesium sulfate test.

Figure 4.2 indicates that the magnesium sulfate soundness test results (mass loss) did not correlate well with the results of the rapid freezing and thawing test (durability factor from AASHTO TP17 [T161 Procedure C]). The percent loss for all size fractions tested for Big Springs-Harmony, Bryan Rock- Shakopee, and Coralville Concrete Ledge-Waterloo was less than 15 percent by weight, which suggests that these sources should exhibit good freeze-thaw durability. However, the durability factors measured for concrete comprising these aggregate sources were 18, 16 and 31, respectively, indicating poor freeze-thaw resistance. Conversely, the magnesium sulfate test suggested that some aggregate sources were nondurable while the freeze-thaw testing indicated that they were durable. For example, concrete comprising Aaland-Zumbrota and Edward Kramer and Sons had measured durability factors of 81 and 79, respectively (indicating durability), while the percentage of mass losses measured from the magnesium sulfate test ranged from 17 to 36 percent and 16 to 29 percent, respectively, for particle sizes less than 25.0 mm (indicating nondurability).

4.3.2 Correlation with Absorption Capacity Test Results

Absorption capacity measurements were performed on the 4.75 to 12.5 mm, 12.5 to 19.0 mm and 19.0 to 37.5 mm size fractions, while magnesium sulfate tests were performed on the 4.75 to 9.50 mm, 9.50 to 12.5 mm, 12.5 to 19.0 mm, 19.0 to 25.0 mm and 25.0 to 37.5 mm size fractions. It was outside the scope of the project to perform further absorption capacity measurements on the small subset of sizes used in the magnesium sulfate testing. Therefore, the absorption capacity results for the three size fractions were used to reflect the individual subsets used for the magnesium sulfate tests. For example, the 19.0 to 37.5 mm absorption capacity values were used to reflect the 19.0 to 25.0 mm and 25.0 to 37.5 mm magnesium sulfate size fractions.

Figure 4.3 presents a plot of the absorption capacities measured for the quarried carbonate coarse aggregate sources versus the percentage of mass loss measured from the magnesium sulfate test for these same sources. In general, the magnesium sulfate test results correlate well with the results of absorption capacity testing, with mass loss measurements increasing approximately linearly with increases in absorption capacity. However, the acceptance/rejection criteria for the two tests (i.e., 15 percent mass loss for the magnesium sulfate test and 1.7 percent maximum allowable absorption) produced conflicting acceptance/rejection recommendations for 24 of the 54 aggregate source/size combinations tested.

4.4 Percentage of Deleterious Material

Aggregate particle types such as carbonates, iron oxides, shales, cherts and sandstones/siltstones are often deleterious in nature, with respect to concrete durability. The percentages of these particle types was determined for the gravel coarse aggregate size fractions subjected to hydraulic fracture testing, as shown in tables 4.5 and 4.6.

Mn/DOT specifications for Class A concrete aggregate limit the carbonate content in gravel sources to 30 percent. According to these criteria, only the Ashwill Kingston and Mark, Underwood sources would be accepted for use, although all 7 gravel sources tested exhibited

Figure 4.3. Absorption capacity versus magnesium sulfate test mass loss (carbonate sources only).

acceptable freeze-thaw durability (durability factor approximately 80 or higher following ASTM C 666 or AASHTO T161).

4.5 Regression Analysis

The small chamber hydraulic fracture test results were modeled using the statistical analysis software package *ARC*, which was developed by Cook and Weisberg of the University of Minnesota Department of Applied Statistics (9).

Separate models were developed for each particle size fraction to predict percent dilation per 100 cycles of freezing and thawing and durability factor using as predictors the cumulative percentages of mass and/or particle counts passing each sieve screen (as described in section 4.1). Table 4.7 presents a list of the models developed and the response variables used in this study.

Table 4.5. Percentage of potentially deleterious aggregate particles in each gravel source (by size fraction).

Aggregate Source	Particle Type														
	Carbonate			Shale			Iron-Oxide			Chert			Sandstone/Siltstone		
	Size Fraction (mm)														
	19.0 - 37.5	12.0 - 19.0	4.75 - 12.0	19.0 - 37.5	12.0 - 19.0	4.75 - 12.0	19.0 - 37.5	12.0 - 19.0	4.75 - 12.0	19.0 - 37.5	12.0 - 19.0	4.75 - 12.0	19.0 - 37.5	12.0 - 19.0	4.75 - 12.0
	Percentages														
Johnson, Henderson	50.9	28.7	34.6	0.0	0.0	0.0	0.0	0.0	0.4	19.3	0.0	0.5	0.0	2.5	2.6
Johnson, Le Sueur	61.7	42.4	45.0	1.9	0.0	0.1	0.0	0.5	0.6	0.0	0.0	0.0	3.1	2.5	0.4
Ashwill, Kingston	N/A	23.0	29.2	N/A	0.4	0.4	N/A	0.0	0.9	N/A	0.0	0.0	N/A	0.0	1.0
Loeffler, Halma	37.3	36.8	53.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mark, Underwood	25.8	20.1	31.4	0.0	0.3	0.0	0.0	0.0	0.2	1.4	0.0	0.0	0.0	0.0	0.0
North Star Kasota	29.3	44.7	47.6	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.6
Northern Con, Luverne	53.8	60.5	60.1	0.0	0.0	0.1	0.0	0.4	0.5	2.5	1.4	0.8	0.0	0.0	0.0

Table 4.6. Total potentially deleterious noncarbonate aggregate particle content in each gravel source (by size fraction).

Aggregate Source	Particle Type		
	All Noncarbonate (Totals)		
	Size Fraction (mm)		
	19.0 - 37.5	12.0 - 19.0	4.75 - 12.0
	Percentages		
Johnson, Henderson	19.3	2.5	3.5
Johnson, Le Sueur	5.0	3.0	1.1
Ashwill, Kingston	N/A	0.4	2.3
Loeffler, Halma	0.0	0.0	0.0
Mark, Underwood	1.4	0.3	0.2
North Star Kasota	0.0	0.0	1.2
Northern Con, Luverne	2.5	1.8	1.4

Table 4.7. Regression analysis matrix.

Explanatory Variables (Cumulative Percentage Passing)	Response Variable	Initial Size Fraction
Mass	Percent Dilation per 100 Cycles	4.75 to 12.5 mm
	Durability Factor	
Particle Counts	Percent Dilation per 100 Cycles	12.5 to 19.0 mm
	Durability Factor	
Mass	Percent Dilation per 100 Cycles	19.0 to 37.5 mm
	Durability Factor	
Particle Counts	Percent Dilation per 100 Cycles	19.0 to 37.5 mm
	Durability Factor	
Mass	Percent Dilation per 100 Cycles	19.0 to 37.5 mm
	Durability Factor	

Appendix E presents a detailed description of the development of each of these models. This section presents the models that were identified as being the best developed for each size fraction and response variable, and documents the selection of the single model that is believed to be best suited for general use with the hydraulic fracture test in accurately predicting the results of freeze-thaw durability testing using AASHTO TP17 (T161 Procedure C).

Table 4.8 lists the regression models developed for each initial size fraction (as described in Appendix E). In general, the correlation between the hydraulic fracture results (i.e., cumulative percentage of mass or particles passing) and rapid freezing and thawing test results increases with increasing particle sizes incorporated in the initial size fraction. These results support past research, where it was found that the greatest amount of freeze-thaw damage occurred with larger size particles due to the greater hydraulic pressures generated from the greater escape distances (4).

The model recommended for further development and use in hydraulic fracture testing is the model of freeze-thaw dilation as a function of the mass measurements obtained during hydraulic fracture testing for the 19 to 37.5 mm (0.75 to 1.5 in) initial size fraction. This model (presented below in equation 4.1) provided excellent correlation with freeze-thaw test results ($r^2 = 0.978$) and offers the advantage of mass measurements, rather than the more time-consuming particle counts. Furthermore, it is based on the largest initial size fraction, which is consistent with traditional thinking that larger aggregate particle sizes generally tend to control freeze-thaw durability in concrete mixtures.

$$\begin{aligned} \% \text{ Dil}/100 = & C^3 * (6.714711\text{E-}9 + 1.493469\text{E-}9 * M_{19 \text{ mm}+ [0.75 \text{ in}+]} \\ & - 2.824751\text{E-}7 * M_{16 - 19 \text{ mm}[0.625 - 0.75 \text{ in}]} + 3.648412\text{E-}7 * M_{13 - 16 \text{ mm}[0.5 - 0.625 \text{ in}]} \\ & - 5.631620\text{E-}7 * M_{9.5 - 13 \text{ mm}[0.375 - 0.5 \text{ in}]} + 2.102003\text{E-}6 * M_{8 - 9.5 \text{ mm}[0.313 - 0.375 \text{ in}]} \\ & - 1.675012\text{E-}6 * M_{4.75 - 8 \text{ mm}[\#4 - 0.313 \text{ in}]} + 1.183342\text{E-}7 * M_{4.75 \text{ mm minus}\{\#4 \text{ minus}\}}) \end{aligned} \quad (\text{Eqn. 4.1})$$

where:

C = Carbonate content (100 percent = 1.00)

$M_{\text{mm}[\text{in}]}$ = mass of particles sized in indicated range as a fraction of
original sample mass (100 percent = 1.00)

$r^2 = 0.978$ ($r^2_{\text{adj}} = 0.957$), $\hat{\sigma} = 0.009934$, $n = 18$

Table 4.8. Summary of regression analysis models.

Initial Size Fraction (mm)	Explanatory Variable (cumulative percentage passing)	R ²	Adj. R ²	General Equation	Table No.*
Percentage of Dilation per 100 Cycles of Rapid Freezing and Thawing					
4.75 to 12.5	Mass	0.333	0.256	$Y = \alpha + C^{2.33} * (\beta_1 * 38M^2 + \beta_2 * 14M^{0.31})$	E.6
12.5 to 19.0	Mass	0.768	0.661	$Y = C^2 * (\alpha + \beta_1 * 58M + \beta_2 * 12M + \beta_3 * 38M + \beta_4 * 516M + \beta_5 * 14M)$	E.8
	Particles	0.806	0.717	$Y = C^{1.9} * (\alpha + \beta_1 * 58P^{0.2} + \beta_2 * 12P^{0.67} + \beta_3 * 38P^{0.61} + \beta_4 * 516P^{0.58} + \beta_5 * 14P^{0.5})$	E.10
19.0 to 37.5	Mass	0.978	0.957	$Y = C^3 * (\alpha + \beta_1 * 34M + \beta_2 * 58M + \beta_3 * 12M + \beta_4 * 38M + \beta_5 * 516M + \beta_6 * 14M + \beta_7 * 4M)$	E.12
	Particles	0.913	0.869	$Y = C^3 * (\alpha + \beta_1 * 1P + \beta_2 * 58P + \beta_3 * 38P + \beta_4 * 516P + \beta_5 * 14P)$	E.14
Durability Factor					
4.75 to 12.5	Mass	0.395	0.284	$Y = \alpha + C^{2.33} * (\beta_1 * 38M^2 + \beta_2 * 516M + \beta_3 * 14M^{0.31})$	E.7
12.5 to 19.0	Mass	0.666	0.547	$Y = \alpha + C * (\beta_1 * 58M + \beta_2 * 12M + \beta_3 * 38M + \beta_4 * 516M + \beta_5 * 14M)$	E.9
	Particles	0.734	0.611	$Y = \alpha + C * (\beta_1 * 38P^{0.61} + \beta_2 * 516P^{0.58}) + \beta_3 * 14P^{0.5} + \beta_4 * 38P^{0.61} + \beta_5 * 12P^{0.67} + \beta_6 * 58P^{0.2}$	E.11
19.0 to 37.5	Mass	0.784	0.676	$Y = \alpha + C^3 * (\beta_1 * 1M^{1.06} + \beta_2 * 34M^{-0.62} + \beta_3 * 58M^{0.27} + \beta_4 * 38M^{0.65} + \beta_5 * 516M^{0.73} + \beta_6 * 14M^{0.84})$	E.13
	Particles	0.949	0.907	$Y = \alpha + C^3 * (\beta_1 * 34P^{0.53} + \beta_2 * 58P^{0.62} + \beta_3 * 12P^{0.61} + \beta_4 * 38P^{0.58} + \beta_5 * 516P^{0.58} + \beta_6 * 14P^{0.55}) + \beta_7 * 4P^{0.5} + \beta_8 * 14P^{0.55}$	E.15

*Coefficient estimates are listed in designated table.

Figure 4.4 presents a plot of predicted dilations using the recommended model versus actual measured dilations for the 18 aggregate sources used to develop the model. The graph shows that the selected model is highly accurate.

4.6 Hydraulic Fracture – Large Chamber

4.6.1 Original Large Chamber Development

The SHRP study recommended that at least 600 to 800 aggregate particles in the 19 to 37 mm [0.75 to 1.50 in] size range be tested in the hydraulic fracture test apparatus to obtain a reliable estimate of aggregate freeze-thaw susceptibility (1). This typically required the testing of three or four replicate samples in the smaller chamber to achieve this particle count. The development

Figure 4.4. Actual versus predicted dilation per 100 cycles using small chamber test results (mass-based model, 19.0 to 37.5-mm original particle sizes).

of a larger chamber was seen as a way to provide more uniform testing of the recommended large number of particles while reducing the need for replicate tests (and while reducing the time required to complete aggregate source testing).

The large chamber was initially developed under the University of Minnesota Graduate School study as described in detail in reference (3). The bullet list describes the modifications which were made to the small chamber design when constructing the large chamber (3):

- the addition of larger valves to allow more rapid discharge of gas and water,
- an increase in the size of the pneumatically actuated ball valve (from 12.5-mm [0.5-in] to 19.0-mm [0.75-in] in diameter),
- the addition of larger pipes to connect the 9.50-mm (0.375-in) exhaust port hole to the larger pneumatically actuated ball valve,

- addition of a stand pipe in the test system to provide a water reservoir and reduce the possibility of gas entering the test chamber, and
- elimination of the 90-degree bend in the pressure release valve system to reduce head loss.

Calibration testing was performed to see if the newly developed large test chamber could achieve a release rate matching the calibration curve. Several attempts were made at matching the small chamber pressure release rate calibration curve, but they met with only limited success as the pressure was generally dissipated over a longer time interval than desired. Figure 4.5 presents a graph illustrating the results of the initial large chamber calibration attempts and shows that the large chamber pressure release rates were significantly lower than the calibration curve.

Hieptas (3) suggested correcting the problem in future studies by using even larger valves and pipes, and increasing the size of the pressure release port. The suggested modifications were made in the current study, as described below.

4.6.2 Large Chamber Modifications

Based on the suggestions described above, the following modifications were made to the large chamber under the current study:

- pressurization piping and valves were increased in size from 12.7 mm (0.50 in) to 19.0 mm (0.75 in) diameter,
- maximum allowable pressure for the actuator was increased from 1.04 MPa (150 psi) to 1.73 MPa (250 psi) and
- exhaust port hole diameter was increased from 12.7 mm (0.50 in) to 22.2 mm (0.875 in).

Calibration tests were performed to see if these modifications to the large chamber allowed the chamber to achieve the desired pressure release rate and match the small chamber calibration curve. Figure 4.6 shows that the calibration was successful with an actuator pressure of 205 psi, resulting in a close match of the calibration curve at durations of 0 to 0.015 and 0.04 to 0.06 seconds. Previous studies have indicated that it is most critical to match the calibration curve at a duration of 0.1 seconds, so the calibration achieved under this study was deemed acceptable.

Figure 4.5. Calibration test data for original Minnesota large chamber (3).

Figure 4.6. Calibration test data for modified large chamber.

4.6.3 Consistency with Small Chamber Results

The hydraulic fracture testing using the large chamber was performed on the initial size fraction (19.0 to 37.5 mm [0.75 to 1.5 in]) of the four aggregate sources previously described in section 3.6 of this report. These sources were selected to provide a range of durability values and were tested in accordance with the procedure described in appendix A.

The percent of original mass retained and percent of original particles retained (POMR and POPR, respectively) on the specified screens for each sample (replicate), along with the average percentages of original mass and particles retained (APOMR and APOPR, respectively) for each source, were calculated using the equations expressed in section 3.5.3. Appendix tables D.1 and D.2 present summaries of the mass measurements and particle counts retained on specified sieves at 0 and 50 cycles for the replicate tests of each source. The normalized mass data (i.e., POMR and APOMR) and particle count data (i.e., POPR and APOPR) are presented in tables D.3 and D.4, respectively, of appendix D.

The cumulative percentages of mass passing each screen were determined according to equations E.3 to E.5, E.7, E.16, E.17 and E.33 to E.35 (see Appendix E). These data were then input into the final model selected for the small chamber (equation 4.1) to see whether the large chamber test results were consistent with those of the small chamber. Figure 4.7 presents the graph of actual versus predicted percentage of dilation per 100 cycles for the small and large chamber data, along with the mean function developed using the small chamber data.

As illustrated in this figure, a fairly close fit is achieved with three of the four sources tested: North Star Kasota (fair freeze-thaw resistance), Johnson Henderson (satisfactory freeze-thaw resistance) and Early Chapel (poor freeze-thaw resistance). However, the mean function does not adequately predict the response for Edward Kramer and Sons, the second source classified as fair freeze-thaw resistance.

In general, the large chamber test results are fairly consistent with those achieved when using the smaller test chamber, thereby indicating the potential use of the large chamber for determining the durability of aggregate sources with varying freezing and thawing resistance. However, due to the limited testing, additional testing would be required to substantiate this conclusion and, therefore, allow the use of the larger chamber over the smaller. As stated previously, the development of the large chamber would provide more uniform testing of a sample (due to the large sample size) and would eliminate the need for replicate tests, thereby reducing the time required to complete testing of a particular aggregate source.

Figure 4.7. Actual versus predicted percent dilation per 100 cycles for large and small chamber test results (mass-based model, 19.0 to 37.5-mm original particle sizes).

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The following conclusions can be drawn from the results of this study:

- The hydraulic fracture test and data analysis procedure described in this report appear to offer a reliable, relatively rapid alternative to determining the potential freeze-thaw durability of concrete coarse aggregate sources.
- The results of regression analyses performed on hydraulic fracture test data show strong correlations between hydraulic fracture test outputs (i.e., cumulative percentage of mass and particle counts passing selected sieve screens) and concrete test specimen dilation data obtained from rapid freezing and thawing tests. The strength of these correlations increases as the top size of the particles in the hydraulic fracture test sample increases, which is consistent with the results of previous studies that link coarse aggregate top size to freeze-thaw durability for potentially nondurable aggregate sources. In this study, the strongest correlations were observed when considering particle mass measurements for samples with initial particle sizes in the 19 to 37.5 mm (0.75 to 1.5 in) range.
- The results of tests performed using the modified large hydraulic fracture test chamber indicate good potential of using the larger chamber in lieu of replicate tests using the smaller chamber, although additional validation work is required.
- For the aggregate sources considered in this study, it appears that the Mn/DOT absorption capacity limit of 1.7 percent on carbonate coarse aggregate successfully eliminated potentially nondurable aggregate sources (as identified through AASHTO TP17 [T161 Procedure C]), although it also appears to eliminate many potentially durable aggregate sources as well. In general, it can be concluded that absorption capacity is not well-correlated with concrete coarse aggregate freeze-thaw durability.
- Mass losses obtained from the magnesium sulfate soundness test (ASTM C 88) generally increased significantly with decreases in test sample initial particle size.
- The magnesium sulfate soundness test results did not generally correlate well with the results of the rapid freezing and thawing tests (AASHTO TP17 [T161 Procedure C], durability factor).

- The magnesium sulfate soundness test results were generally well correlated with the absorption capacity of carbonate aggregate sources (see figure 4.3), but the acceptance/rejection criteria currently used for these two tests often fail to provide consistent acceptance/rejection recommendations for carbonate aggregates intended for use in concrete paving mixtures.
- The hydraulic fracture test and data analysis procedure described in this report appear to offer better correlation with the results of rapid freezing and thawing tests (AASHTO TP17 [T161 Procedure C]) than either the magnesium sulfate test (ASTM C88) or the current Mn/DOT absorption capacity criterion for carbonate aggregate sources.

5.2 Recommendations

- Additional freeze-thaw and hydraulic fracture tests should be performed using the small test chamber on additional aggregate sources to further validate and refine the final model identified in this study for predicting the freeze-thaw durability of concrete coarse aggregate. The hydraulic fracture tests should focus primarily of the use of 19 to 38 mm (0.75 to 1.5 in) test sample particle sizes, since this larger particle size appears to provide the best indications of potential freeze-thaw resistance. Furthermore, the hydraulic fracture tests should involve mainly mass measurements rather than particle counts because the mass measurement model produced the best correlations with freeze-thaw data, and because mass measurements are accomplished much more quickly than particle counts.
- Additional hydraulic fracture testing should be performed using the modified large hydraulic fracture test chamber using mass measurements and particles in the 19 to 38 mm (0.75 to 1.5 in) range to further validate the large test chamber.
- Additional tests and research should be performed to verify and determine the nature of the outlier hydraulic fracture test results obtained for the Shiely Grey Cloud (Larson) source that was tested using the small chamber in this study.
- Similarly, additional tests and research should be performed to verify and determine the nature of the outlier hydraulic fracture test results obtained for the Edward Kramer and Sons source, which was an outlier in the large chamber testing performed during the project and did not produce the same sort of test results obtained using the small chamber in this study.

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APPENDIX A

Modified Hydraulic Fracture Test Procedures

APPENDIX A

Modified Hydraulic Fracture Test Procedures

A.1. SCOPE

A.1.1 This test method covers the resistance of aggregates to fracture under the effect of internal pressure expelling water from aggregate pores. The procedure is intended to assist in the identification of aggregates that cause deterioration in concrete when exposed to repeated cycles of freezing and thawing (D-cracking).

A.1.2 This procedure may involve hazardous materials, operations, and equipment. This procedure does not purport to address all the safety problems associated with its use. It is the responsibility of whoever uses this procedure to consult and establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

A.2. REFERENCED DOCUMENTS

A.2.1 AASHTO Standards

T 2	Sampling Aggregates
M 92	Wire Cloth Sieves for Testing Purposes
M 231	Weights and Balances Used in the Testing of Highway Materials

A.2.2 ASTM Standards

C 702	Method for Reducing Field Samples of Aggregate to Testing Size
D 3665	Practice for Random Sampling of Construction Materials

A.3. SIGNIFICANCE AND USE

A.3.1 As noted in the scope, the procedure described in this method is intended to aid in the identification of coarse aggregate samples that may be susceptible to D-cracking. Aggregate particles that exhibit a high rate of fracturing under repeated pressurization cycles are considered

to be more susceptible to D-cracking when critically saturated and subject to cycles of freezing and thawing in field applications.

A.3.2 The relatively short time required for completion of this procedure (approximately eight working days) makes it suitable for use as a screening test to identify aggregate sources that should be subjected to more traditional (and more time consuming) testing prior to approval.

A.3.3 The results of this test, like D-cracking susceptibility, appear to be sensitive to the size of the aggregate particles tested. Therefore, this test may be appropriate for identifying aggregate particle size reductions that are necessary to avoid D-cracking in field applications.

A.3.4 The results of this test are also sensitive to the number of soft or nondurable particles (e.g., sandstone, clay ironstone, etc.) in the test sample. Therefore, this test may be appropriate for determining the amount of durable aggregate that must be blended with nondurable aggregate to produce a blend with sufficiently low D-cracking potential to provide acceptable performance.

A.4. APPARATUS

A.4.1 Tumbling Apparatus

A.4.1.1 The tumbling apparatus (hereafter referred to as the tumbler) shall consist of a rubber drum (for holding the sample) and a motorized drive unit, similar to the one shown in figure A.1.

Note 1 - Suitable tumblers of various sizes are available commercially for polishing rocks.

A.4.1.2 The rubber drum shall have inside dimensions of approximately 171 mm (6.75 in) in diameter by 203 mm (8 in) deep. The inside shall be faceted to facilitate tumbling of the aggregate particles. The drum shall have a removable cover (so that the sample can be placed in the drum), and the cover should not interfere with the rotation of the drum when it is mounted in or on the motorized drive unit.

A.4.1.3 The motorized drive unit shall be capable of rotating the drum about its cylindrical axis at a rate of 30 ± 5 revolutions per minute.

Figure A.1. Photo of typical tumbler drum and drive unit.

A.4.2 Pressurization Apparatus

A.4.2.1 The pressurization apparatus shall consist of: a pressure chamber able to safely withstand operating pressures of 10,000-kPa (1500-psi); a compressed nitrogen source; an adjustable pressure regulator with gauge having an output capacity of up to 10,000-kPa (1500-psi); appropriate valves and fittings to permit filling with water and draining, and pressurization/rapid pressure release; and a stand to permit a 135 degree rotation of the pressurization apparatus.

A.4.2.2 The inside surfaces of the pressure chamber shall be suitably treated to prevent the physical fracture of aggregates by the expansion and contraction of the chamber during pressurization/de-pressurization cycles.

Note 2 - For a cylindrical steel chamber with 25-mm (1-in) thick walls and having inside dimensions of 254 mm (10 in) diameter by 51 mm (2 in.) high, a neoprene rubber sheet with a thickness of 0.8 mm (0.0313 in.) glued to the insides of the chamber lid and base has proven sufficient. No treatment was necessary for the inside wall of the cylinder, as shown in figure A.2.

Note 3 - Shop-built pressure chambers are not recommended for use in this test due to the difficulty in obtaining pressure-tight seals at the high pressures involved, as well as the hazards associated with high pressures. If a shop-built pressure chamber is used, it should be pressure-certified to provide a safety factor of at least 5 to 1.

Figure A.2. Photo of small chamber interior with neoprene lining.

A.4.2.3 The pressure chamber shall be fitted with necessary valves and fittings to permit the application of pressure from the nitrogen source (pressurization valve), release of pressure (pressure release valve), filling with water (fill valve), and draining (drain valve). Additional valves and fittings may be provided where appropriate by the equipment manufacturer in order to achieve the necessary pressure release rate (see section A.4.2.5).

A.4.2.4 A pressure regulator and gauge that attaches directly to a compressed nitrogen cylinder shall be provided. The regulator shall have a capacity of 10,000 kPa (1500 psi). The gauge shall have a precision of 0.25 percent of full scale.

A.4.2.5 The apparatus should be capable of producing a drop in pressure of at least 2,100 kPa (300 psi.) during a time interval of 0.01 second when the pressure release valve is open. This drop in pressure is termed the pressure release rate for a time duration of 0.01 second. The procedure for measuring the pressure release rate is described in Appendix A of the SHRP C 391 report.

A.4.3 Drying Oven

The drying oven should allow free circulation of air through the oven and should be capable of maintaining a temperature of $110^{\circ}\text{C} \pm 5^{\circ}\text{C}$ ($230^{\circ}\text{F} \pm 9^{\circ}\text{F}$).

A.4.4 Balance

The balance should conform to the requirements of AASHTO M 231 for the class of general purpose balance required for determining the principal mass of the sample being tested.

A.5. SPECIAL SOLUTIONS REQUIRED

A.5.1 A solution of alkylalkoxysilane in water (referred to as silane solution) is used in Step A.7.3 as part of the sample preparation.

A.5.2 Appropriate precautions should be observed in handling the silane solution.

Note 4 - An appropriate silane solution is available commercially as Enviroseal 40 from Hydrozo, Inc. Other sources may provide suitable results as well.

Note 5 - Some aggregates absorb water at a very rapid rate, which prevents them from fracturing in the following test procedure. The silane treatment described in Step 7.3 reduces the absorption rate by effectively making the aggregates more hydrophobic. This treatment has been demonstrated to have no effect on the hydraulic fracture performance of aggregates with slower absorption rates.

A.6. SAMPLES

A.6.1 Representative samples of aggregate sources should be obtained by appropriate means and in accordance with accepted procedures such as AASHTO T 2 and ASTM C 702 and D 3665.

A.6.2 Each aggregate sample to be tested should be screened to produce one or more test samples consisting of the desired particle sizes (step A.7.1 below). The size fraction recommended for indicating D-cracking potential contains only particles retained on the 19-mm (0.75-in.) sieve.

A.6.3 Replicate specimens may be run to determine test variability, and sufficient material should be collected in the initial sample to provide the necessary number of particles in each desired size range. Preliminary work has indicated that 600 to 800 particles must be tested to provide a reasonably accurate estimate of coarse aggregate D-cracking potential.

A.7. PREPARATION OF TEST SAMPLE

A.7.1 Obtain a sample of the desired particle size distribution (e.g., 19 mm [0.75 in] plus) by sieving to refusal using appropriate wire screens (AASHTO M 92). Individual test samples should contain sufficient quantities of aggregate to fill the pressure chamber.

A.7.2 The aggregate sample should be washed thoroughly and dried to a constant mass at a temperature of $110^{\circ}\text{C} \pm 5^{\circ}\text{C}$ ($230^{\circ}\text{F} \pm 9^{\circ}\text{F}$), and allowed to cool to room temperature.

Note 6 - Adequate ventilation should be supplied for the following three steps. The use of a fume hood may be appropriate.

A.7.3 Place the aggregate sample in the silane solution, making sure that all aggregate particles are submerged. Allow the specimen to remain in the silane solution for 30 ± 5 seconds.

A.7.4 Remove the specimen from the silane solution and allow excess solution to drain for five minutes.

Note 7 - Strainers suitable for immersing the aggregate in the silane solution and draining are readily obtainable from restaurant supply sources. An example is shown in figure A.3.

Note 8 - The silane solution may be re-used if it is placed in a sealed container between uses. The solution should be discarded if it begins to thicken.

Figure A.3. Photo of silane-treated aggregate sample in double boiler.

A.7.5 Dry the specimens to a constant mass at a temperature of $110^{\circ}\text{C} \pm 5^{\circ}\text{C}$ ($230^{\circ}\text{F} \pm 9^{\circ}\text{F}$), and allow to cool to room temperature for one hour.

A.8. TEST PROCEDURE

A.8.1 Place enough aggregate in the tumbler to fill it approximately half way. Tumble the aggregate for 1 minute (± 5 seconds). Remove the aggregate from the tumbler and discard any

pieces passing the 4.75-mm (#4) sieve. Repeat until the entire aggregate test sample has been tumbled.

A.8.2 For noncarbonate aggregate sources, a qualified petrographer should examine the sample to estimate the carbonate content (by percent mass) of the aggregate sample.

A.8.3 Fill the test chamber with aggregate particles (as shown in figure A.4), being careful not to overfill the chamber (which may result in particle fracture due to closure of the chamber rather than due to the hydraulic fracture mechanism). Remove the aggregate from the test chamber and determine the mass of the test sample. Record this number as the initial sample mass.

Figure A.4. Photo of large test chamber (filled with aggregate) and strike-off bar.

A.8.4 Place the specimen in the pressure chamber and close the chamber as directed in the manufacturer's instructions (see figure A.5). Rotate the apparatus from the filling position (typically horizontal) to the testing (typically vertical) position.

Figure A.5. Photo of small chamber closed in horizontal position.

A.8.5 Close the pressure valve and open the main valve on the nitrogen tank. The pressure regulator should be set to the pressure indicated on the calibration sheet provided with the equipment.

Note 9 - A minimum pressure of 7,930 kPa (1150 psi.) is currently recommended. Further work may justify a different chamber pressure.

A.8.6 Connect the drain line to the pressure release valve. Open the fill and pressure release valves and fill the pressure chamber with water using the procedures described in the manufacturer's instructions. After the chamber is full and as water is flowing through the chamber and drain line, remove air bubbles from the chamber walls by pivoting the chamber to approximately 45 degrees on either side of the testing position and tapping the exterior of the chamber smartly with a rubber mallet. After the chamber has been filled and the air bubbles removed, close the pressure release valve, close the fill valve, and turn off the water supply. Remove the drain line from the end of the pressure release valve. This process should be completed in 2 minutes (± 5 seconds).

A.8.7 After ensuring that all chamber valves are initially closed, pressurize the chamber for 5 minutes (± 5 seconds) by opening the pressure valve. Adjust the pressure regulator as necessary to maintain the required pressure. At about 4.75 minutes, close the pressure valve.

A.8.8 After 5 minutes (± 5 seconds) of pressurization, release the pressure to produce the prescribed pressure release rate by opening the pressure valve as described in the equipment manufacturer's instructions. Figures A.6 and A.7 show a small test chamber ready for pressure release and during pressure release, respectively.

A.8.9 Re-attach the drain line to the pressure release valve (now open), open the fill valve, and turn on the water supply to refill the chamber with water as before. Allow water to fill for approximately 30 seconds, rotating the chamber to 45 degrees either side of the test position and using the rubber mallet to remove any gas bubbles from the sides of the chamber. Close the pressure release valve, then the fill valve and turn off the water supply. Remove the drain line.

A.8.10 Re-pressurize the chamber after a total elapsed time of 1 minute (± 5 seconds) without pressure. Adjust the regulator as necessary to maintain the desired pressure. This pressurization time is 2 minutes (± 5 seconds). After about 1.75 minutes, close the pressure valve.

A.8.11 Release the pressure after 2 minutes (± 5 seconds) by rapidly opening the pressure valve (as described in step 8.6 above).

A.8.12 Repeat steps A.8.7 through A.8.9 eight additional times for a total of ten pressurization cycles. Rotate the pressure chamber back to the aggregate fill position to drain the chamber and remove the aggregate test sample.

Figure A.6. Photo of small test chamber (with muffler) ready for pressure release.

Figure A.7. Photo of small test chamber during pressure release (without muffler).

A.8.13 Turn off the valve on the nitrogen bottle and open the drain valve. Drain the water from the pressure chamber by slowly opening the pressure valve and allowing the compressed gas in the line to force water out of the chamber.

A.8.14 Open the chamber and remove the test sample. Dry the specimen to a constant mass at a temperature of $110^{\circ}\text{C} \pm 5^{\circ}\text{C}$ ($230^{\circ}\text{F} \pm 9^{\circ}\text{F}$), and allow it to cool at room temperature for one hour.

A.8.15 Place enough aggregate in the tumbler to fill it approximately half way. Tumble the aggregate for 1 minute (± 5 seconds). Remove the aggregate from the tumbler, retaining all particles. Repeat until the entire aggregate test sample has been tumbled. Sieve the sample and determine (to the nearest 0.1g) the masses retained on the 16.0-mm (0.625-in), 12.5-mm (0.5-in), 9.5-mm (0.375-in.), 8-mm (0.3125-in) and 4.75-mm (#4) sieves. Record these values, noting the number, i, of pressurization cycles completed. Remove the particles passing the 4.75-mm (#4) sieve from the testing procedure, determine their mass to the nearest tenth of a gram, and save in a labeled container.

A.8.16 Repeat Steps A.8.4 through A.8.15 for a total of 50 pressurization cycles per test sample.

A.8.17 If necessary, test replicate samples of the same aggregate source until a sufficient quantity of material has been tested to provide a reasonably accurate estimate of coarse aggregate D-cracking potential (currently considered to be 600-800 aggregate particles).

A.9. ANALYSIS OF DATA

A.9.1 Determine the combined mass of particles retained on the 16.0-mm (0.625-in), 12.5-mm (0.5-in), 9.5-mm (0.375-in.), 8-mm (0.3125-in.) and 4.75-mm (#4) sieves along with the mass of all particles passing the 4.75-mm (#4) sieve after 50 cycles of pressurization for all replicate test samples representing a given aggregate source.

A.9.2 Determine the relative proportion of the masses of the various particle sizes to the original test sample mass (e.g., the original mass = 1.00 and all final masses range from 0.00 to 1.00 and sum to 1.00).

A.9.3 Estimate the freeze-thaw dilation that would occur in a concrete prism containing this aggregate source and tested using AASHTO TP17 using the following equation:

$$\begin{aligned} \% \text{ Dil}/100 = & C^3 * (6.714711\text{E-}9 + 1.493469\text{E-}9 * M_{19 \text{ mm [0.75 in]}} \text{ plus} \\ & - 2.824751\text{E-}7 * M_{16 - 19 \text{ mm[0.625 - 0.75 in]}} + 3.648412\text{E-}7 * M_{13 - 16\text{mm[0.5 - 0.625 in]}} \\ & - 5.631620\text{E-}7 * M_{9.5 - 13\text{mm[0.375 - 0.5 in]}} + 2.102003\text{E-}6 * M_{8 - 9.5\text{mm[0.313 - 0.375 in]}} \\ & - 1.675012\text{E-}6 * M_{4.75 - 8 \text{ mm[\#4 - 0.313 in]}} + 1.183342\text{E-}7 * M_{4.75 \text{ mm [\#4] minus}}) \end{aligned}$$

where:

C = Carbonate content (100 percent = 1.00)

$M_{\text{mm[in]}}$ = relative proportion of the masses of the various particle sizes
to the original test sample mass

$$r^2 = 0.978 \text{ (} r^2_{\text{adj}} = 0.957 \text{), } \hat{\sigma} = 0.009934, n = 18$$

A.9.4 Apply appropriate acceptance or rejection criteria to the results of the analysis to determine the suitability of the given aggregate source or to suggest the need for additional or supplemental testing using this or other tests of concrete coarse aggregate freeze-thaw damage potential (e.g., ASTM C 666/AASHTO T161 or TP17, etc.).

APPENDIX B

PCC and Coarse Aggregate Property Data

Table B.1. PCC mix proportions, air and slump data for freeze-thaw test specimens.

Aggregate Source	Batch Number	Coarse Aggregate (kg/m ³)	Fine Aggregate (kg/m ³)	Cement (kg/m ³)	Water (kg/m ³)	A/E (mL/100 kgc)	w/c Ratio	Cement Type	Slump (mm)	Plastic Air Content (%)
QUARRIED										
Aaland, Zumbrota	1	1095	712	350	156	0.037**	0.45	I	83	6.4
	2					0.037**			95	8.6
Big Springs, Harmony	1	1058	712	350	140	0.083	0.40	I	45	3.5
Bryan Rock, Shakopee	1	1114	712	350	142	0.027**	0.41	I	51	3.5
	2				147	0.033**			64	4.6
Coralville Concrete Ledge, Waterloo	1-11	1092	704	319	144	0.012**	0.45	I	76-84	4.4-7.4
Early Chapel	1	1093	712	350	141	0.027	0.40	I	45	3.6
	2				142	0.033			32	3.7
Edward Kramer & Sons, Burnsville	1	1040	712	350	140	0.077	0.40	I	60	4.9
Goldberg, Rochester	1	1072	712	350	140	0.073	0.40	I	64	4.4
Michigan Limestone, Cedarville Plant	1	1146	712	350	140	0.073	0.40	I	64	5.9
Osmundson, Grand Meadow	1	1078	712	350	141	0.021**	0.40	I	32	4.6
	2					0.024**			38	6.0*/5.0
Shiely Grey Cloud (Larson)	1	1006	712	350	140	0.073	0.40	I	57	5.3
SMC Mankato	1	1014	712	350	140	0.068	0.40	I	57	4.8
Swedberg	1	1048	712	350	140	0.077	0.40	I	38	3.5
Ulland Northwood, Iowa	1	1134	712	350	140	0.073	0.40	I	51	3.5
GRAVEL										
Ashwill, Kingston	1	1093	712	350	140	0.077	0.40	I	51	4.9
Johnson, Henderson	1	1100	712	350	140	0.053	0.40	I	60	4.4
Johnson Le Sueur	1	1094	712	350	140	0.073	0.40	I	57	5.7
Loeffler, Halma	1	1098	712	350	140	0.073	0.40	I	70	5.9
Mark, Underwood	1	1128	712	350	140	0.073	0.40	I	83	6.4
Northern Con, Luverne	1	1083	712	350	140	0.073	0.40	I	108	7.0
North Star Kasota	1	1101	712	350	140	0.045	0.40	I	83	4.5

* Possible leak in air meter (reading was initially at 6.1%); ran another plastic air test 15 minutes later due to difficulties with air test apparatus.

** ConChem air-entrainment admixture was used for these batches; for all other batches Daravair 1000 was used as the air-entraining admixture.

Table B.2. Strength and durability data for each mixture.

Source	Batch Number	Compressive Strength, 14-day (MPa)	Static Modulus of Elasticity, 14-day (GPa)	Durability Factor	Dilation ¹ (%)	Dilation / 100 Cycles (%)
QUARRIED						
Aaland, Zumbrota	1	30.0		47.6	0.072	0.030
		32.4		82.0	0.046	0.015
				81.9	-0.008	-0.003
	2	24.6		96.1	0.021	0.007
				94.8	0.015	0.005
Big Springs, Harmony	1	40.6	30.9	23.5	0.015	0.013
		39.7	32.0	11.0	0.010	0.018
		41.8	31.3	14.8	0.110	0.149
				15.3	0.005	0.006
				25.5	0.082	0.064
Bryan Rock, Shakopee	1	46.4		17.2	0.107	0.124
		47.1		13.8	0.068	0.099
	2	44.3		20.9	0.103	0.098
				21.8	0.117	0.107
				6.2	0.050	0.161
Coralville Concrete Ledge, Waterloo ²	1	39.5	31.9	56.8	0.101	0.036
	2	35.4	27.4	47.0	0.100	0.043
	3	38.4	27.9	41.4	0.082	0.040
	4	37.2	27.9	39.0	0.094	0.048
	5	44.2	31.2	44.0	0.119	0.054
				35.4	0.103	0.058
	6	44.3	25.4	18.0	0.115	0.128
	7	43.5	31.2	14.6	0.087	0.119
	8	43.5	31.2	34.0	0.099	0.058
	9	44.3	31.4	11.0	0.106	0.041
	10	44.2	30.7	28.2	0.092	0.065
	11	42.5	31.9	36.2	0.112	0.062
	12	42.4	31.6	11.0	0.110	0.200
Early Chapel	1	41.5		33.8	0.091	0.054
		44.4		43.9	0.099	0.045
				38.0	0.086	0.045
	2	44.6		32.0	0.076	0.048
				32.6	0.093	0.057
Edward Kramer & Sons, Burnsville	1	20.6	19.2	88.9	0.025	0.008
		38.3	22.0	83.8	0.039	0.013
		31.5	23.4	87.1	0.046	0.015
				61.6	0.078	0.026
				71.7	0.077	0.026

Table B.2. Strength and durability data for each mixture (continued).

Source	Batch Number	Compressive Strength, 14-day (MPa)	Static Modulus of Elasticity, 14-day (GPa)	Durability Factor	Dilation ¹ (%)	Dilation / 100 Cycles (%)
QUARRIED						
Goldberg, Rochester	1	41.7	26.9	95.8	0.009	0.003
		43.5	27.9	95.6	0.014	0.005
		43.1	28.1	96.1	0.008	0.003
				94.8	0.011	0.004
				93.9	0.018	0.006
Michigan Limestone, Cedarville Plant	1	35.6	31.8	100.1	0.006	0.002
		33.1	31.5	99.4	0.005	0.002
		34.1	29.6	99.6	0.002	0.001
				99.2	-0.009	-0.003
				98.4	0.005	0.002
Osmundson, Grand Meadow	1	46.2		66.9	0.077	0.026
		45.7		72.1	0.065	0.022
	2	49.5		86.8	0.040	0.013
				89.4	0.038	0.013
				76.9	0.057	0.019
Shiely Grey Cloud (Larson)	1	44.3	26.6	99.4	0.012	0.004
		44.3	27.9	99.6	0.009	0.003
		43.4	26.5	100.2	0.006	0.002
				97.3	0.014	0.005
				97.3	0.014	0.005
SMC Mankato	1	35.9	25.6	8.4	0.054	0.129
		36.4	23.5	20.2	0.095	0.094
		37.2	23.6	5.2	0.036	0.138
				20.7	0.080	0.077
				12.5	0.075	0.119
Swedberg	1	30.4	28.7	27.5	0.089	0.064
		33.2	28.2	27.3	0.097	0.071
		35.0	27.7	23.1	0.112	0.097
				27.3	0.127	0.093
				25.7	0.079	0.062
Ulland Northwood, Iowa	1	39.9	34.1	97.7	-0.014	-0.005
		42.0	35.0	95.5	-0.007	-0.002
				97.3	-0.014	-0.005
				98.0	0.006	0.002
				96.6	-0.013	-0.004
				96.4	0.012	0.004
				98.5	0.006	0.002

Table B.2. Strength and durability data for each mixture (continued).

Source	Batch Number	Compressive Strength, 14-day (MPa)	Static Modulus of Elasticity, 14-day (GPa)	Durability Factor	Dilation ¹ (%)	Dilation / 100 Cycles (%)
GRAVEL						
Ashwill, Kingston	1	38.1	31.1	95.2	0.003	0.001
		38.2	30.7	98.2	0.020	0.007
		38.9	30.2	97.4	0.008	0.003
				96.4	0.012	0.004
				98.5	0.006	0.002
Johnson, Henderson	1	34.2	28.6	78.3	0.029	0.010
		35.6	29.3	88.1	0.017	0.006
		36.6	29.0	89.7	0.015	0.005
				96.7	0.010	0.003
				98.2	0.010	0.003
Johnson Le Sueur	1	33.0	29.9	95.6	0.011	0.004
		29.2	29.4	93.4	0.023	0.008
		28.6	27.2	96.9	0.011	0.004
				80.2	0.036	0.012
				75.5	0.034	0.011
Loeffler, Halma	1	33.7	30.3	98.9	0.008	0.003
		35.2	31.4	93.7	0.019	0.006
		34.5	29.6	95.3	0.015	0.005
				96.6	0.015	0.005
				85.2	0.031	0.010
Mark, Underwood	1	30.9	31.1	97.9	0.007	0.002
		28.3	30.7	93.5	0.026	0.009
		31.4	27.6	93.1	0.015	0.005
				98.5	0.014	0.005
				94.7	-0.002	-0.001
Northern Con, Luverne	1	30.6	23.0	77.0	0.032	0.011
		31.0	24.2	75.3	0.020	0.007
		31.0	24.2	88.1	0.025	0.008
				88.0	0.024	0.008
				90.7	0.019	0.006
North Star Kasota	1	35.1	30.9	77.6	0.025	0.008
		35.4	29.2	73.8	0.025	0.008
		33.5	30.3	89.4	0.021	0.007
				68.6	0.045	0.015
				87.7	0.042	0.014

1 Percent dilation is at failure (when the relative dynamic modulus reaches 60 percent) or 300 cycles which ever came first.

2 Static modulus of elasticity and compression tests were performed at 28 days.

Table B.3. Unit weight and void content data for aggregate sources.

Aggregate Source	Trial No.	Unit Weight (lb/ft ³)		Unit Weight (kg/m ³)		Void Content (%)	
		Result	Avg.	Result	Avg.	Result	Avg.
Aaland, Zumbrota	1	93.6	94.3	1518.2	1529.4	40.0	39.5
	2	95.0		1540.6		39.1	
Ashwill, Kingston	1	98.4	97.5	1595.1	1580.7	40.1	40.6
	2	96.6		1566.3		41.2	
Big Springs, Harmony	1	96.2	96.6	1559.9	1566.3	39.5	39.2
	2	97.0		1572.7		39.0	
Bryan Rock, Shakopee	1	93.6	93.7	1518.2	1519.8	39.8	39.7
	2	93.8		1521.4		39.7	
Cedarville Plant, Michigan Limestone	1	102.5	102.3	1662.3	1659.1	40.5	40.6
	2	102.1		1655.9		40.7	
Coralville Concrete Ledge, Waterloo							
Early Chapel, Iowa	1	91.1	91.7	1476.6	1486.2	41.1	40.7
	2	92.3		1495.8		40.3	
Edward Kramer & Sons, Burnsville	1	98.4	98.5	1595.1	1596.7	37.1	37.0
	2	98.6		1598.3		36.9	
Goldberg, Rochester	1	100.7	100.4	1633.5	1627.1	37.5	37.7
	2	100.0		1620.7		38.0	
Johnson, Henderson	1	106.1	105.9	1720.0	1716.8	35.8	35.9
	2	105.7		1713.6		36.1	
Johnson, Le Sueur	1	106.9	107.2	1732.8	1737.6	35.0	34.8
	2	107.5		1742.4		34.6	
Loeffler, Halma	1	103.5	103.8	1678.4	1683.2	37.3	37.1
	2	104.1		1688.0		36.9	
Mark, Underwood	1	109.2	108.8	1771.2	1764.8	35.5	35.7
	2	108.4		1758.4		36.0	
Northern Con, Luverne	1	106.5	106.5	1726.4	1726.4	34.5	34.5
	2	106.5		1726.4		34.5	
North Star Kasota	1	108.4	108.6	1758.4	1761.6	34.4	34.3
	2	108.8		1764.8		34.2	
Osmundson, Grand Meadow	1	91.9	92.3	1489.4	1495.8	38.9	38.6
	2	92.6		1502.2		38.4	
Shiely Grey Cloud (Larson)	1	93.2	93.4	1511.8	1515.0	38.3	38.2
	2	93.6		1518.2		38.1	
SMC, Mankato	1	94.2	93.4	1527.8	1515.0	38.1	38.7
	2	92.6		1502.2		39.2	
Swedberg	1	93.8	93.5	1521.4	1516.6	40.4	40.6
	2	93.2		1511.8		40.8	
Ulland, Northwood	1	98.6	99.2	1598.3	1607.9	42.2	41.8
	2	99.8		1617.5		41.5	

Table B.4. As-produced sieve analysis for project aggregate sources.

Sieve Size (mm)	Percentage of Mass Retained									
	Aaland, Zumbrota	Ashwill, Kingston	Big Springs, Harmony	Bryan Rock, Shakopee	Cedarville Plant, Michigan Limestone	Coralville Concrete Ledge, Waterloo	Early Chapel, Iowa	Edward Kramer & Sons, Burnsville	Goldberg, Rochester	Loeffler, Halma
25.0	16.39	0.00	26.14	16.21	10.23	0.00	2.02	14.99	17.74	0.00
19.0	15.22	0.00	12.00	15.76	21.78	17.35	26.42	22.75	20.82	30.91
16.0	17.03	13.10	16.40	15.69	14.50	18.09	20.60	16.44	15.08	18.32
12.5	15.59	35.93	19.88	19.45	22.10	20.70	16.25	14.42	14.93	15.77
9.5	21.30	33.31	10.74	26.02	25.62	17.62	20.52	12.28	11.62	17.07
8.0	7.81	7.94	4.41	5.56	4.10	8.33	8.69	6.29	6.22	8.34
6.35	4.87	5.53	5.54	1.25	1.31	9.26	4.25	7.10	7.17	7.50
4.75	1.77	4.18	4.88	0.06	0.35	8.65	1.25	5.74	6.43	2.08
pan	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total:	100	100	100	100	100	100	100	100	100	100

Sieve Size (mm)	Percentage of Mass Retained									
	Johnson, Henderson	Johnson, LeSueur	Mark, Underwood	Northern Con, Luverne	North Star Kasota	Osmundson, Grand Meadow	Shiely Gray Cloud (Larson)	SMC, Mankato	Swedberg	Ulland, Northwood
25.0	19.15	11.66	13.93	22.52	14.46	11.78	13.40	27.15	11.22	11.46
19.0	12.87	24.83	20.60	10.44	21.00	18.21	20.66	9.86	22.28	20.20
16.0	11.96	17.50	17.89	22.38	19.39	15.49	21.36	13.36	21.92	14.51
12.5	21.67	16.57	17.35	17.48	16.75	21.45	13.20	17.18	11.82	17.10
9.5	18.45	10.58	14.65	9.15	9.14	19.72	16.65	18.47	13.51	13.39
8.0	9.00	7.30	7.75	6.20	5.04	5.08	8.88	6.56	6.47	7.17
6.35	6.04	8.33	6.22	8.58	7.24	6.88	4.71	4.83	7.12	9.28
4.75	0.86	3.24	1.60	3.25	6.98	1.39	1.14	2.60	5.66	6.89
pan	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total:	100	100	100	100	100	100	100	100	100	100

APPENDIX C

Hydraulic Fracture Test Results – Small Chamber

Table C.1. HFT results (mass retained) for small chamber samples (4.75 to 12.5 mm [#4 to 0.5 in]).

Aggregate Source	Source Type	Replicate Number	Mass Retained (g)									
			Total	After 50 Cycles								
				Sieve Sizes								
				25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Ashwill, Kingston	Gravel	1	2846.6	0.0	0.0	0.0	0.0	1697.8	508.6	341.4	204.6	75.1
		2	2874.7	0.0	0.0	0.0	0.0	1694.4	561.5	321.0	235.1	49.4
		3										
		4	2862.2	0.0	0.0	0.0	0.0	1290.9	612.0	503.3	366.4	74.3
		5	2912.0	0.0	0.0	0.0	0.0	1650.5	572.6	333.5	270.6	72.4
		1-5	11495.5	0.0	0.0	0.0	0.0	6333.6	2254.7	1499.2	1076.7	271.2
Big Springs, Harmony	Quarried	1	2744.1	0.0	0.0	0.0	0.0	802.8	553.1	733.2	510.2	135.1
		2	2896.5	0.0	0.0	0.0	0.0	727.2	582.4	805.8	665.7	102.6
		3	2815.2	0.0	0.0	0.0	0.0	899.1	621.2	655.2	566.8	48.4
		4										
		5										
		1-5	8455.8	0.0	0.0	0.0	0.0	2429.1	1756.7	2194.2	1742.7	286.1
Bryan Rock	Quarried	1	3154.0	0.0	0.0	0.0	0.0	2420.6	578.6	130.9	8.0	3.0
		2	3165.6	0.0	0.0	0.0	0.0	2353.0	632.2	147.6	7.4	10.3
		3	3166.2	0.0	0.0	0.0	0.0	2366.4	626.7	129.8	4.6	10.9
		4	3126.8	0.0	0.0	0.0	0.0	2246.9	678.7	162.5	9.3	18.5
		5										
		1-5	12612.6	0.0	0.0	0.0	0.0	9386.9	2516.2	570.8	29.3	42.7
Cedarville Plant	Quarried	1	3065.7	0.0	0.0	0.0	0.0	2342.5	530.2	150.7	22.8	4.4
		2	3081.7	0.0	0.0	0.0	0.0	2314.8	523.9	188.8	37.0	7.6
		3										
		4	3025.7	0.0	0.0	0.0	0.0	2161.1	599.1	173.6	60.1	17.0
		5										
		1-5	9173.1	0.0	0.0	0.0	0.0	6818.4	1653.2	513.1	119.9	29.0

Table C.1. HFT results (mass retained) for small chamber samples (4.75 to 12.5 mm [#4 to 0.5 in]) (continued).

Aggregate Source	Source Type	Replicate Number	Mass Retained (g)									
			Total	0 Cycles								
				After 50 Cycles								
				Sieve Sizes								
				25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Early Chapel	Quarried	1	3089.6	0.0	0.0	0.0	0.0	1718.3	793.9	433.2	120.4	12.7
		2	3050.7	0.0	0.0	0.0	0.0	1697.7	822.2	399.8	90.5	21.4
		3	3090.8	0.0	0.0	0.0	0.0	1582.3	903.5	447.8	113.8	15.3
		4	2977.6	0.0	0.0	0.0	0.0	1735.6	756.1	353.2	90.2	19.4
		5	3050.6	0.0	0.0	0.0	0.0	1383.4	904.2	527.0	198.4	23.4
		1-5	15259.3	0.0	0.0	0.0	0.0	8117.3	4179.9	2161.0	613.3	92.2
Edward Kramer & Sons	Quarried	1	2621.4	0.0	0.0	0.0	0.0	832.6	557.6	669.0	468.1	69.7
		2	2482.7	0.0	0.0	0.0	0.0	675.7	607.3	596.2	501.7	71.2
		3										
		4	2450.0	0.0	0.0	0.0	0.0	645.6	517.0	650.5	541.6	64.2
		5	2529.5	0.0	0.0	0.0	0.0	711.4	603.0	615.1	493.2	80.8
		1-5	10083.6	0.0	0.0	0.0	0.0	2865.3	2284.9	2530.8	2004.6	285.9
Goldberg, Rochester	Quarried	1	2584.9	0.0	0.0	0.0	0.0	645.2	560.8	694.6	516.8	128.5
		2	2633.7	0.0	0.0	0.0	0.0	739.6	648.3	627.7	526.7	63.5
		3	2569.9	0.0	0.0	0.0	0.0	747.6	544.7	622.6	552.4	79.8
		4	2571.2	0.0	0.0	0.0	0.0	590.6	565.0	619.7	597.4	168.1
		5										
		1-5	10359.7	0.0	0.0	0.0	0.0	2723.0	2318.8	2564.6	2193.3	439.9
Grand Meadow	Quarried	1	3190.5	0.0	0.0	0.0	0.0	1643.6	729.8	648.2	112.6	10.9
		2	3161.9	0.0	0.0	0.0	0.0	1707.8	747.7	549.5	128.5	16.9
		3	3149.8	0.0	0.0	0.0	0.0	1547.3	780.1	580.8	190.9	16.9
		4	2809.2	0.0	0.0	0.0	0.0	1260.8	737.2	572.2	194.1	23.3
		5										
		1-5	12311.4	0.0	0.0	0.0	0.0	6159.5	2994.8	2350.7	626.1	68.0

Table C.1. HFT results (mass retained) for small chamber samples (4.75 to 12.5 mm [#4 to 0.5 in]) (continued).

Aggregate Source	Source Type	Replicate Number	Mass Retained (g)									
			Total	0 Cycles								
				After 50 Cycles								
				Sieve Sizes								
				25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Halma	Gravel	1	3147.7	0.0	0.0	0.0	0.0	1404.7	839.6	707.5	180.8	10.9
		2	3082.5	0.0	0.0	0.0	0.0	1311.2	864.5	676.8	210.3	11.5
		3	3059.3	0.0	0.0	0.0	0.0	1389.3	764.2	667.3	212.3	17.6
		4	3056.7	0.0	0.0	0.0	0.0	1454.0	642.9	753.9	188.4	11.3
		5	3065.0	0.0	0.0	0.0	0.0	1371.7	784.4	690.3	189.9	16.8
		1-5	15411.2	0.0	0.0	0.0	0.0	6930.9	3895.6	3495.8	981.7	68.1
Johnson, Henderson	Gravel	1	3115.1	0.0	0.0	0.0	0.0	1563.0	813.1	648.8	71.0	5.8
		2	3394.6	0.0	0.0	0.0	0.0	1526.2	1025.7	695.5	110.9	16.9
		3										
		4	3233.7	0.0	0.0	0.0	0.0	1455.6	1012.5	637.0	103.5	11.4
		5	3263.7	0.0	0.0	0.0	0.0	1560.2	955.8	619.7	100.6	21.5
		1-5	13007.1	0.0	0.0	0.0	0.0	6105.0	3807.1	2601.0	386.0	55.6
Johnson, Le Sueur	Gravel	1	2973.0	0.0	0.0	0.0	0.0	817.0	707.9	1011.7	381.0	45.8
		2	2925.1	0.0	0.0	0.0	0.0	894.8	777.0	848.4	345.8	40.7
		3										
		4	2949.1	0.0	0.0	0.0	0.0	884.2	802.2	825.1	373.2	42.4
		5	3039.0	0.0	0.0	0.0	0.0	928.8	860.9	909.5	297.6	35.5
		1-5	11886.2	0.0	0.0	0.0	0.0	3524.8	3148.0	3594.7	1397.6	164.4
Mark, Underwood	Gravel	1	3058.3	0.0	0.0	0.0	0.0	1284.4	805.6	737.1	200.3	26.9
		2	3034.8	0.0	0.0	0.0	0.0	1451.6	812.0	596.2	158.3	10.0
		3	3067.3	0.0	0.0	0.0	0.0	1295.3	912.6	652.3	190.5	10.2
		4	3092.3	0.0	0.0	0.0	0.0	1287.5	856.4	722.4	204.8	15.8
		5										
		1-5	12252.7	0.0	0.0	0.0	0.0	5318.8	3386.6	2708.0	753.9	62.9

Table C.1. HFT results (mass retained) for small chamber samples (4.75 to 12.5 mm [#4 to 0.5 in]) (continued).

Aggregate Source	Source Type	Replicate Number	Mass Retained (g)									
			Total	After 50 Cycles								
				Sieve Sizes								
				0 Cycles								
				25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Northern Con, Luverne	Gravel	1	3058.8	0.0	0.0	0.0	0.0	949.8	704.8	1066.4	312.2	18.0
		2	3148.2	0.0	0.0	0.0	0.0	856.1	694.8	1128.2	448.9	14.0
		3										
		4	3079.8	0.0	0.0	0.0	0.0	786.9	791.5	1019.6	451.8	18.1
		5										
		1-5	9286.8	0.0	0.0	0.0	0.0	2592.8	2191.1	3214.2	1212.9	50.1
North Star Kasota	Gravel	1	3083.5	0.0	0.0	0.0	0.0	923.8	514.1	914.0	664.8	34.9
		2	3122.0	0.0	0.0	0.0	0.0	864.0	563.7	841.8	801.8	24.7
		3										
		4	3093.2	0.0	0.0	0.0	0.0	848.3	584.6	780.9	800.9	67.5
		5	3095.1	0.0	0.0	0.0	0.0	846.3	608.8	791.2	799.5	46.3
		1-5	12393.8	0.0	0.0	0.0	0.0	3482.4	2271.2	3327.9	3067.0	173.4
Shiely Grey Cloud	Quarried	1	3029.3	0.0	0.0	0.0	0.0	1399.3	807.4	608.7	127.6	42.2
		2	2978.6	0.0	0.0	0.0	0.0	1309.4	973.7	485.8	137.5	39.8
		3	2948.7	0.0	0.0	0.0	0.0	1096.1	1068.2	586.0	149.8	27.4
		4	2967.6	0.0	0.0	0.0	0.0	1301.1	1007.6	484.7	92.0	44.2
		5										
		1-5	11924.2	0.0	0.0	0.0	0.0	5105.9	3856.9	2165.2	506.9	153.6
SMC Mankato	Quarried	1	2876.7	0.0	0.0	0.0	0.0	1370.8	626.5	531.6	273.4	48.9
		2	2818.3	0.0	0.0	0.0	0.0	1506.6	628.1	393.7	200.3	58.8
		3										
		4	2700.5	0.0	0.0	0.0	0.0	1251.6	635.6	463.9	236.2	82.4
		5	2869.4	0.0	0.0	0.0	0.0	1267.6	693.6	515.3	299.7	60.9
		1-5	11264.9	0.0	0.0	0.0	0.0	5396.6	2583.8	1904.5	1009.6	251.0

Table C.1. HFT results (mass retained) for small chamber samples (4.75 to 12.5 mm [#4 to 0.5 in]) (continued).

Aggregate Source	Source Type	Replicate Number	Mass Retained (g)									
			Total	0 Cycles								
				After 50 Cycles								
				Sieve Sizes								
				25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Swedberg	Quarried	1	2688.9	0.0	0.0	0.0	0.0	950.7	539.1	640.6	474.3	71.2
		2	2597.3	0.0	0.0	0.0	0.0	935.2	592.2	554.6	452.1	53.4
		3	2559.8	0.0	0.0	0.0	0.0	885.6	572.7	594.8	435.1	55.6
		4	2577.3	0.0	0.0	0.0	0.0	841.3	520.5	651.1	488.0	59.9
		5	2601.3	0.0	0.0	0.0	0.0	877.1	593.1	560.0	480.7	75.5
		1-5	13024.6	0.0	0.0	0.0	0.0	4489.9	2817.6	3001.1	2330.2	315.6
Ulland Northwood	Quarried	1	2944.6	0.0	0.0	0.0	0.0	832.9	627.4	848.4	533.6	92.4
		2	2844.5	0.0	0.0	0.0	0.0	637.9	648.6	803.5	692.5	44.2
		3	2953.1	0.0	0.0	0.0	0.0	769.6	765.7	792.5	579.9	30.3
		4	2855.9	0.0	0.0	0.0	0.0	593.9	583.1	936.8	673.2	56.0
		5	2964.4	0.0	0.0	0.0	0.0	866.3	715.7	754.3	576.1	40.5
		1-5	14562.5	0.0	0.0	0.0	0.0	3700.6	3340.5	4135.5	3055.3	263.4
Waterloo	Quarried	1	3091.5	0.0	0.0	0.0	0.0	827.6	541.2	821.3	801.3	91.0
		2	2935.5	0.0	0.0	0.0	0.0	807.3	658.8	712.8	685.0	44.2
		3	2945.5	0.0	0.0	0.0	0.0	884.8	663.9	709.7	621.5	42.7
		4	2970.9	0.0	0.0	0.0	0.0	1108.7	741.6	622.2	454.4	26.7
		5	2872.0	0.0	0.0	0.0	0.0	865.1	618.8	678.0	653.3	40.1
		1-5	14815.4	0.0	0.0	0.0	0.0	4493.5	3224.3	3544.0	3215.5	244.7
Zumbrota	Quarried	1	3178.6	0.0	0.0	0.0	0.0	1742.6	658.4	564.7	158.0	33.5
		2	3182.3	0.0	0.0	0.0	0.0	1805.0	742.6	442.9	140.7	30.9
		3	3162.6	0.0	0.0	0.0	0.0	1678.7	802.5	439.9	174.4	39.7
		4	2790.0	0.0	0.0	0.0	0.0	1237.6	790.2	458.9	197.4	73.0
		5	3050.5	0.0	0.0	0.0	0.0	1468.8	804.6	469.1	204.2	74.4
		1-5	15364.0	0.0	0.0	0.0	0.0	7932.7	3798.3	2375.5	874.7	251.5

Table C.2. HFT results (normalized, mass retained) for small chamber samples (4.75 to 12.5 mm [#4 to 0.5 in]).

Aggregate Source	Source Type	Replicate Number	Normalized Mass Retained (%)								
			Sieve Sizes								
			25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Ashwill, Kingston	Gravel	1	0.000	0.000	0.000	0.000	59.643	17.867	11.993	7.188	2.638
		2	0.000	0.000	0.000	0.000	58.942	19.532	11.166	8.178	1.718
		3									
		4	0.000	0.000	0.000	0.000	45.102	21.382	17.584	12.801	2.596
		5	0.000	0.000	0.000	0.000	56.679	19.663	11.453	9.293	2.486
		1-5	0.000	0.000	0.000	0.000	55.096	19.614	13.042	9.366	2.359
Big Springs, Harmony	Quarried	1	0.000	0.000	0.000	0.000	29.255	20.156	26.719	18.593	4.923
		2	0.000	0.000	0.000	0.000	25.106	20.107	27.820	22.983	3.542
		3	0.000	0.000	0.000	0.000	31.937	22.066	23.274	20.134	1.719
		4									
		5									
		1-5	0.000	0.000	0.000	0.000	28.727	20.775	25.949	20.610	3.383
Bryan Rock	Quarried	1	0.000	0.000	0.000	0.000	76.747	18.345	4.150	0.254	0.095
		2	0.000	0.000	0.000	0.000	74.330	19.971	4.663	0.234	0.325
		3	0.000	0.000	0.000	0.000	74.739	19.793	4.100	0.145	0.344
		4	0.000	0.000	0.000	0.000	71.859	21.706	5.197	0.297	0.592
		5									
		1-5	0.000	0.000	0.000	0.000	74.425	19.950	4.526	0.232	0.339
Cedarville Plant	Quarried	1	0.000	0.000	0.000	0.000	76.410	17.295	4.916	0.744	0.144
		2	0.000	0.000	0.000	0.000	75.114	17.000	6.126	1.201	0.247
		3									
		4	0.000	0.000	0.000	0.000	71.425	19.800	5.738	1.986	0.562
		5									
		1-5	0.000	0.000	0.000	0.000	74.330	18.022	5.594	1.307	0.316

Table C.2. HFT results (normalized, mass retained) for small chamber samples (4.75 to 12.5 mm [#4 to 0.5 in]) (cont.).

Aggregate Source	Source Type	Replicate Number	Normalized Mass Retained (%)								
			Sieve Sizes								
			25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Early Chapel	Quarried	1	0.000	0.000	0.000	0.000	55.616	25.696	14.021	3.897	0.411
		2	0.000	0.000	0.000	0.000	55.650	26.951	13.105	2.967	0.701
		3	0.000	0.000	0.000	0.000	51.194	29.232	14.488	3.682	0.495
		4	0.000	0.000	0.000	0.000	58.289	25.393	11.862	3.029	0.652
		5	0.000	0.000	0.000	0.000	45.348	29.640	17.275	6.504	0.767
		1-5	0.000	0.000	0.000	0.000	53.196	27.392	14.162	4.019	0.604
Edward Kramer & Sons	Quarried	1	0.000	0.000	0.000	0.000	31.762	21.271	25.521	17.857	2.659
		2	0.000	0.000	0.000	0.000	27.216	24.461	24.014	20.208	2.868
		3									
		4	0.000	0.000	0.000	0.000	26.351	21.102	26.551	22.106	2.620
		5	0.000	0.000	0.000	0.000	28.124	23.839	24.317	19.498	3.194
		1-5	0.000	0.000	0.000	0.000	28.415	22.660	25.098	19.880	2.835
Goldberg, Rochester	Quarried	1	0.000	0.000	0.000	0.000	24.960	21.695	26.871	19.993	4.971
		2	0.000	0.000	0.000	0.000	28.082	24.616	23.833	19.998	2.411
		3	0.000	0.000	0.000	0.000	29.091	21.195	24.227	21.495	3.105
		4	0.000	0.000	0.000	0.000	22.970	21.974	24.102	23.234	6.538
		5									
		1-5	0.000	0.000	0.000	0.000	26.285	22.383	24.756	21.171	4.246
Grand Meadow	Quarried	1	0.000	0.000	0.000	0.000	51.515	22.874	20.317	3.529	0.342
		2	0.000	0.000	0.000	0.000	54.012	23.647	17.379	4.064	0.534
		3	0.000	0.000	0.000	0.000	49.124	24.767	18.439	6.061	0.537
		4	0.000	0.000	0.000	0.000	44.881	26.242	20.369	6.909	0.829
		5									
		1-5	0.000	0.000	0.000	0.000	50.031	24.325	19.094	5.086	0.552

Table C.2. HFT results (normalized, mass retained) for small chamber samples (4.75 to 12.5 mm [#4 to 0.5 in]) (cont.).

Aggregate Source	Source Type	Replicate Number	Normalized Mass Retained (%)								
			Sieve Sizes								
			25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Halma	Gravel	1	0.000	0.000	0.000	0.000	44.626	26.673	22.477	5.744	0.346
		2	0.000	0.000	0.000	0.000	42.537	28.045	21.956	6.822	0.373
		3	0.000	0.000	0.000	0.000	45.412	24.980	21.812	6.939	0.575
		4	0.000	0.000	0.000	0.000	47.568	21.032	24.664	6.164	0.370
		5	0.000	0.000	0.000	0.000	44.754	25.592	22.522	6.196	0.548
		1-5	0.000	0.000	0.000	0.000	44.973	25.278	22.684	6.370	0.442
Johnson, Henderson	Gravel	1	0.000	0.000	0.000	0.000	50.175	26.102	20.828	2.279	0.186
		2	0.000	0.000	0.000	0.000	44.960	30.216	20.488	3.267	0.498
		3									
		4	0.000	0.000	0.000	0.000	45.013	31.311	19.699	3.201	0.353
		5	0.000	0.000	0.000	0.000	47.805	29.286	18.988	3.082	0.659
		1-5	0.000	0.000	0.000	0.000	46.936	29.269	19.997	2.968	0.427
Johnson, Le Sueur	Gravel	1	0.000	0.000	0.000	0.000	27.481	23.811	34.030	12.815	1.541
		2	0.000	0.000	0.000	0.000	30.590	26.563	29.004	11.822	1.391
		3									
		4	0.000	0.000	0.000	0.000	29.982	27.202	27.978	12.655	1.438
		5	0.000	0.000	0.000	0.000	30.563	28.328	29.928	9.793	1.168
		1-5	0.000	0.000	0.000	0.000	29.655	26.484	30.243	11.758	1.383
Mark, Underwood	Gravel	1	0.000	0.000	0.000	0.000	41.997	26.341	24.102	6.549	0.880
		2	0.000	0.000	0.000	0.000	47.832	26.756	19.645	5.216	0.330
		3	0.000	0.000	0.000	0.000	42.229	29.753	21.266	6.211	0.333
		4	0.000	0.000	0.000	0.000	41.636	27.695	23.361	6.623	0.511
		5									
		1-5	0.000	0.000	0.000	0.000	43.409	27.640	22.101	6.153	0.513

Table C.2. HFT results (normalized, mass retained) for small chamber samples (4.75 to 12.5 mm [#4 to 0.5 in]) (cont.).

Aggregate Source	Source Type	Replicate Number	Normalized Mass Retained (%)								
			Sieve Sizes								
			25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Northern Con, Luverne	Gravel	1	0.000	0.000	0.000	0.000	31.051	23.042	34.863	10.207	0.588
		2	0.000	0.000	0.000	0.000	27.193	22.070	35.836	14.259	0.445
		3									
		4	0.000	0.000	0.000	0.000	25.550	25.700	33.106	14.670	0.588
		5									
		1-5	0.000	0.000	0.000	0.000	27.919	23.594	34.610	13.060	0.539
North Star Kasota	Gravel	1	0.000	0.000	0.000	0.000	29.959	16.673	29.642	21.560	1.132
		2	0.000	0.000	0.000	0.000	27.675	18.056	26.963	25.682	0.791
		3									
		4	0.000	0.000	0.000	0.000	27.425	18.900	25.246	25.892	2.182
		5	0.000	0.000	0.000	0.000	27.343	19.670	25.563	25.831	1.496
		1-5	0.000	0.000	0.000	0.000	28.098	18.325	26.851	24.746	1.399
Shiely Grey Cloud	Quarried	1	0.000	0.000	0.000	0.000	46.192	26.653	20.094	4.212	1.393
		2	0.000	0.000	0.000	0.000	43.960	32.690	16.310	4.616	1.336
		3	0.000	0.000	0.000	0.000	37.172	36.226	19.873	5.080	0.929
		4	0.000	0.000	0.000	0.000	43.844	33.953	16.333	3.100	1.489
		5									
		1-5	0.000	0.000	0.000	0.000	42.820	32.345	18.158	4.251	1.288
SMC Mankato	Quarried	1	0.000	0.000	0.000	0.000	47.652	21.778	18.480	9.504	1.700
		2	0.000	0.000	0.000	0.000	53.458	22.286	13.969	7.107	2.086
		3									
		4	0.000	0.000	0.000	0.000	46.347	23.536	17.178	8.747	3.051
		5	0.000	0.000	0.000	0.000	44.176	24.172	17.958	10.445	2.122
		1-5	0.000	0.000	0.000	0.000	47.906	22.937	16.906	8.962	2.228

Table C.2. HFT results (normalized, mass retained) for small chamber samples (4.75 to 12.5 mm [#4 to 0.5 in]) (cont.).

Aggregate Source	Source Type	Replicate Number	Normalized Mass Retained (%)								
			Sieve Sizes								
			25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Swedberg	Quarried	1	0.000	0.000	0.000	0.000	35.356	20.049	23.824	17.639	2.648
		2	0.000	0.000	0.000	0.000	36.007	22.801	21.353	17.407	2.056
		3	0.000	0.000	0.000	0.000	34.596	22.373	23.236	16.997	2.172
		4	0.000	0.000	0.000	0.000	32.643	20.196	25.263	18.935	2.324
		5	0.000	0.000	0.000	0.000	33.719	22.800	21.528	18.479	2.902
		1-5	0.000	0.000	0.000	0.000	34.473	21.633	23.042	17.891	2.423
Ulland Northwood	Quarried	1	0.000	0.000	0.000	0.000	28.286	21.307	28.812	18.121	3.138
		2	0.000	0.000	0.000	0.000	22.426	22.802	28.247	24.345	1.554
		3	0.000	0.000	0.000	0.000	26.061	25.929	26.836	19.637	1.026
		4	0.000	0.000	0.000	0.000	20.796	20.417	32.802	23.572	1.961
		5	0.000	0.000	0.000	0.000	29.223	24.143	25.445	19.434	1.366
		1-5	0.000	0.000	0.000	0.000	25.412	22.939	28.398	20.981	1.809
Waterloo	Quarried	1	0.000	0.000	0.000	0.000	26.770	17.506	26.566	25.919	2.944
		2	0.000	0.000	0.000	0.000	27.501	22.443	24.282	23.335	1.506
		3	0.000	0.000	0.000	0.000	30.039	22.539	24.094	21.100	1.450
		4	0.000	0.000	0.000	0.000	37.319	24.962	20.943	15.295	0.899
		5	0.000	0.000	0.000	0.000	30.122	21.546	23.607	22.747	1.396
		1-5	0.000	0.000	0.000	0.000	30.330	21.763	23.921	21.704	1.652
Zumbrota	Quarried	1	0.000	0.000	0.000	0.000	54.823	20.714	17.766	4.971	1.054
		2	0.000	0.000	0.000	0.000	56.720	23.335	13.918	4.421	0.971
		3	0.000	0.000	0.000	0.000	53.080	25.375	13.909	5.514	1.255
		4	0.000	0.000	0.000	0.000	44.358	28.323	16.448	7.075	2.616
		5	0.000	0.000	0.000	0.000	48.149	26.376	15.378	6.694	2.439
		1-5	0.000	0.000	0.000	0.000	51.632	24.722	15.461	5.693	1.637

Table C.3. HFT results (mass retained) for small chamber samples (12.5 to 19.0 mm [0.5 to 0.75 in]).

Aggregate Source	Source Type	Replicate Number	Mass Retained (g)									
			Total	After 50 Cycles								
				Sieve Sizes								
				25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Ashwill, Kingston	Gravel	1	3090.7	0.0	0.0	610.7	1889.5	564.3	7.1	2.9	0.8	7.7
		2	3076.2	0.0	0.0	700.8	1848.1	512.3	0.5	1.1	0.0	6.8
		3	3093.6	0.0	0.0	633.7	1976.9	459.9	2.7	2.1	1.9	14.4
		4	3059.7	0.0	0.0	618.4	1964.0	435.2	6.7	1.9	2.2	15.5
		5	3000.0	0.0	0.0	569.9	1927.0	463.6	2.4	1.1	0.0	11.5
		1-5	15320.2	0.0	0.0	3133.5	9605.5	2435.3	19.4	9.1	4.9	55.9
Big Springs, Harmony	Quarried	1	3051.1	0.0	0.0	1092.0	1542.9	381.9	1.4	2.5	0.5	3.9
		2	3122.0	0.0	0.0	1122.7	1509.4	464.9	0.0	0.6	1.2	12.7
		3	3167.5	0.0	0.0	1003.1	1714.6	411.7	4.8	3.3	1.4	16.5
		4	3093.5	0.0	0.0	938.9	1617.5	492.0	2.0	2.2	1.5	22.9
		5	3146.4	0.0	0.0	1311.2	1393.9	399.5	1.2	1.8	0.9	17.8
		1-5	15580.5	0.0	0.0	5467.9	7778.3	2150.0	9.4	10.4	5.5	73.8
Bryan Rock	Quarried	1	3170.3	0.0	0.0	1345.0	1581.2	225.7	0.0	0.0	0.0	3.1
		2	3002.0	0.0	0.0	1108.8	1599.3	269.1	0.0	0.0	0.0	11.1
		3	3101.8	0.0	0.0	948.4	1773.7	337.4	0.0	0.0	0.0	10.4
		4	3216.6	0.0	0.0	1051.5	1739.2	403.3	0.0	0.0	0.0	9.5
		5	3015.1	0.0	0.0	894.7	1653.4	419.3	0.0	0.3	0.2	26.6
		1-5	15505.8	0.0	0.0	5348.4	8346.8	1654.8	0.0	0.3	0.2	60.7
Cedarville Plant	Quarried	1	3095.2	0.0	0.0	766.1	1559.3	747.0	4.4	0.7	0.0	6.0
		2	3039.8	0.0	0.0	978.5	1425.9	611.9	4.0	2.1	0.0	13.4
		3	3132.2	0.0	0.0	933.7	1650.1	521.5	5.0	0.5	0.0	11.2
		4	3021.2	0.0	0.0	871.4	1641.7	486.6	0.0	1.2	0.1	6.5
		5	3065.5	0.0	0.0	848.7	1559.5	623.4	4.0	0.3	0.3	15.8
		1-5	15353.9	0.0	0.0	4398.4	7836.5	2990.4	17.4	4.8	0.4	52.9

Table C.3. HFT results (mass retained) for small chamber samples (12.5 to 19.0 mm [0.5 to 0.75 in]) (continued).

			Mass Retained (g)									
			0 Cycles	After 50 Cycles								
				Sieve Sizes								
Aggregate Source	Source Type	Replicate Number	Total	25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Early Chapel	Quarried	1	3163.3	0.0	0.0	1558.3	1450.6	136.7	0.0	0.4	0.4	5.6
		2	3186.9	0.0	0.0	1134.0	1699.3	321.4	1.2	3.0	0.0	17.5
		3	3451.5	0.0	0.0	1425.7	1614.0	342.5	11.0	3.0	1.7	27.6
		4	3011.8	0.0	0.0	1407.6	1359.0	216.9	0.0	0.0	0.0	14.8
		5	3255.2	0.0	0.0	1388.2	1528.6	260.0	10.1	6.6	3.1	35.3
		1-5	16068.7	0.0	0.0	6913.8	7651.5	1277.5	22.3	13.0	5.2	100.8
Edward Kramer & Sons	Quarried	1	2813.8	0.0	0.0	1143.0	1268.9	341.3	3.9	5.5	3.2	27.5
		2	2789.4	0.0	0.0	981.8	1338.8	409.4	4.6	0.8	1.4	28.9
		3*	2897.8	0.0	0.0	1222.3	1287.6	313.0	5.3	2.1	2.0	35.6
		4	2790.9	0.0	0.0	924.6	1295.1	485.8	3.7	4.1	1.3	46.7
		5										
		1-5	8394.1	0.0	0.0	3049.4	3902.8	1236.5	12.2	10.4	5.9	103.1
Goldberg, Rochester	Quarried	1	2782.7	0.0	0.0	1025.5	1248.0	436.1	3.0	0.5	0.7	30.3
		2										
		3	2978.6	0.0	0.0	1063.9	1446.7	406.5	3.7	0.8	0.4	30.7
		4	2969.2	0.0	0.0	1118.5	1273.9	508.3	2.8	1.6	0.5	41.2
		5	2870.9	0.0	0.0	1029.3	1307.4	448.6	0.7	5.8	1.5	47.9
		1-5	11601.4	0.0	0.0	4237.2	5276.0	1799.5	10.2	8.7	3.1	150.1
Grand Meadow	Quarried	1	3103	0.0	0.0	989.5	1667.5	337.5	2.1	1.1	0.8	3.2
		2	3064.6	0.0	0.0	695.0	1835.7	498.5	0.7	0.9	0.0	12.1
		3	3262.8	0.0	0.0	766.1	1837.0	615.9	3.8	1.4	0.5	21.3
		4	3147.3	0.0	0.0	716.7	1853.1	536.5	2.2	0.0	0.7	15.2
		5	3062.2	0.0	0.0	754.7	1773.8	481.3	6.6	0.4	0.9	22.4
		1-5	15639.9	0.0	0.0	3922.0	8967.1	2469.7	15.4	3.8	2.9	74.2

Table C.3. HFT results (mass retained) for small chamber samples (12.5 to 19.0 mm [0.5 to 0.75 in]) (continued).

Aggregate Source	Source Type	Replicate Number	Mass Retained (g)									
			0 Cycles	After 50 Cycles								
				Sieve Sizes								
			Total	25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Halma	Gravel	1	3120.5	0.0	11.2	1367.8	1512.1	206.5	0.0	0.9	0.6	8.0
		2	3023.0	0.0	0.0	1419.8	1455.8	126.2	2.5	1.4	1.1	10.2
		3	3028.4	0.0	0.0	1418.8	1415.0	173.6	1.2	1.7	0.3	9.1
		4	3051.4	0.0	0.0	1341.2	1469.8	221.4	2.3	0.0	0.2	6.8
		5	3126.3	0.0	0.0	1438.3	1482.9	130.0	1.3	1.3	0.9	9.6
		1-5	12229.1	0.0	0.0	5618.1	5823.5	651.2	7.3	4.4	2.5	35.7
Johnson, Henderson	Gravel	1	3011.7	0.0	0.0	1269.7	1553.9	153.3	8.8	0.4	0.3	4.1
		2	3335.8	0.0	0.0	1073.0	1883.4	348.9	1.3	2.4	0.7	10.3
		3	3287.7	0.0	0.0	1125.6	1758.1	378.5	3.1	0.7	0.7	8.9
		4	3337.3	0.0	0.0	1034.6	1880.2	388.4	5.0	2.5	1.1	13.8
		5	3350.6	0.0	0.0	973.2	1859.7	466.2	4.5	0.0	0.8	8.8
		1-5	16323.1	0.0	0.0	5476.1	8935.3	1735.3	22.7	6.0	3.6	45.9
Johnson, Le Sueur	Gravel	1	3050.3	0.0	0.0	1408.2	1363.0	256.9	0.3	3.8	0.8	6.9
		2	3018.8	0.0	0.0	1252.2	1507.5	216.3	3.2	5.7	2.5	18.0
		3	3017.7	0.0	0.0	1304.7	1486.2	201.4	3.9	1.2	3.4	13.7
		4	3080.1	0.0	0.0	1379.5	1473.2	197.3	1.8	1.5	1.6	12.8
		5	3094.2	0.0	0.0	1210.8	1631.3	217.3	1.1	2.0	0.6	12.9
		1-5	15261.1	0.0	0.0	6555.4	7461.2	1089.2	10.3	14.2	8.9	64.3
Mark, Underwood	Gravel	1	3081.9	0.0	0.0	1543.7	1321.8	195.1	3.1	1.6	0.4	2.9
		2	3164.8	0.0	0.0	1606.9	1402.5	136.9	2.4	3.7	1.0	9.4
		3	3087.6	0.0	0.0	1491.2	1414.2	159.2	0.0	2.1	1.0	11.2
		4	3013.2	0.0	0.0	1237.5	1592.8	161.4	3.6	1.3	0.6	8.3
		5	3034.2	0.0	0.0	950.0	1789.0	277.5	0.0	0.9	0.9	6.2
		1-5	15381.7	0.0	0.0	6829.3	7520.3	930.1	9.1	9.6	3.9	38.0

Table C.3. HFT results (mass retained) for small chamber samples (12.5 to 19.0 mm [0.5 to 0.75 in]) (continued).

			Mass Retained (g)									
			0 Cycles	After 50 Cycles								
				Sieve Sizes								
Aggregate Source	Source Type	Replicate Number	Total	25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Northern Con, Luverne	Gravel	1	2901.0	0.0	0.0	1517.2	1170.6	178.3	2.3	0.5	0.6	15.5
		2	2919.8	0.0	0.0	1131.3	1526.4	211.5	12.0	3.2	1.4	12.6
		3	3020.4	0.0	0.0	1548.9	1228.3	217.5	2.5	1.2	0.2	10.9
		4	3119.8	0.0	0.0	1805.3	1107.1	152.2	6.1	3.3	1.1	16.0
		5	3119.2	0.0	0.0	1371.3	1556.6	183.5	4.1	0.5	1.2	11.0
		1-5	15080.2	0.0	0.0	7374.0	6589.0	943.0	27.0	8.7	4.5	66.0
North Star Kasota	Gravel	1	3077.3	0.0	0.0	1675.4	1300.9	42.1	5.6	2.1	2.0	2.3
		2	3314.2	0.0	0.0	1414.4	1704.6	178.0	3.6	1.8	2.0	8.8
		3	3468.8	0.0	0.0	1695.6	1551.0	193.3	3.9	1.3	2.8	11.4
		4	3159.0	0.0	0.0	1419.2	1548.9	161.0	2.3	0.0	0.2	10.5
		5	3538.4	0.0	0.0	1824.1	1490.2	176.6	7.5	3.4	2.7	28.7
		1-5	16557.7	0.0	0.0	8028.7	7595.6	751.0	22.9	8.6	9.7	61.7
Shiely Grey Cloud	Quarried	1	3054.7	0.0	0.0	1484.0	1238.6	290.5	4.7	4.8	2.0	13.2
		2	3011.1	0.0	0.0	1580.4	1143.9	239.8	0.0	0.0	0.1	26.1
		3	3051.7	0.0	0.0	1362.6	1213.7	428.6	0.0	1.6	0.7	24.8
		4	2961.2	0.0	0.0	1524.6	993.2	374.9	0.9	0.5	0.3	42.7
		5	3051.1	0.0	0.0	1540.5	1131.3	320.4	1.1	1.1	1.4	46.5
		1-5	15129.8	0.0	0.0	7492.1	5720.7	1654.2	6.7	8.0	4.5	153.3
SMC Mankato	Quarried	1	3028.5	0.0	0.0	920.4	1606.6	419.2	7.1	2.9	2.2	34.9
		2	3034.7	0.0	0.0	973.2	1580.7	375.8	9.3	7.4	3.6	54.0
		3	3034.3	0.0	0.0	1044.7	1563.1	355.8	1.6	1.4	2.6	38.5
		5	3026.7	0.0	0.0	856.9	1674.5	387.8	5.5	6.6	2.1	53.8
		1-5	12124.2	0.0	0.0	3795.2	6424.9	1538.6	23.5	18.3	10.5	181.2

Table C.3. HFT results (mass retained) for small chamber samples (12.5 to 19.0 mm [0.5 to 0.75 in]) (continued).

Aggregate Source	Source Type	Replicate Number	Mass Retained (g)									
			Total	After 50 Cycles								
				Sieve Sizes								
				0 Cycles								
				25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Swedberg	Quarried	1	2812.9	0.0	0.0	1491.0	1077.0	196.4	6.2	5.0	3.5	13.7
		2	2835.6	0.0	0.0	1592.6	950.5	255.1	4.7	3.4	3.8	15.1
		3	2798.2	0.0	0.0	1569.9	994.9	204.6	2.0	2.0	2.9	15.3
		4	2677.5	0.0	0.0	1563.0	953.2	131.2	3.6	1.8	1.1	14.9
		5	2917.1	0.0	0.0	1460.2	1221.0	200.7	3.6	3.4	2.8	14.9
		1-5	14041.3	0.0	0.0	7676.7	5196.6	988.0	20.1	15.6	14.1	73.9
Ulland Northwood	Quarried	1	3024.0	0.0	0.0	846.9	1611.9	535.2	0.0	2.4	0.2	6.1
		2	3042.5	0.0	0.0	957.0	1537.9	507.6	6.0	5.2	1.2	15.1
		3	3050.1	0.0	0.0	1027.5	1510.5	492.8	0.7	0.7	0.6	10.0
		4	2794.6	0.0	0.0	960.8	1396.0	405.1	3.3	0.5	1.2	14.5
		5	3025.6	0.0	0.0	1089.9	1515.2	393.6	0.8	1.1	0.5	14.5
		1-5	14936.8	0.0	0.0	4882.1	7571.5	2334.3	10.8	9.9	3.7	60.2
Waterloo	Quarried	1	2966.2	0.0	0.0	854.2	1530.6	559.7	3.0	2.0	0.0	5.6
		2	3066.4	0.0	0.0	974.1	1651.5	414.3	2.8	0.5	0.8	12.0
		3	2929.6	0.0	0.0	936.6	1524.1	444.7	1.0	1.1	0.0	7.9
		4	2934.3	0.0	0.0	1024.2	1498.7	391.5	0.0	0.0	0.0	6.9
		5	3008.0	0.0	0.0	782.8	1551.7	645.1	0.0	0.2	0.2	9.4
		1-5	14904.5	0.0	0.0	4571.9	7756.6	2455.3	6.8	3.8	1.0	41.8
Zumbrota	Quarried	1	3156.2	0.0	0.0	1424.9	1319.1	353.6	5.5	1.5	2.4	27.9
		2	3146.6	0.0	0.0	1221.6	1533.2	307.5	9.4	5.9	2.6	42.5
		3	3134.7	0.0	0.0	1376.4	1434.3	240.4	2.4	4.0	1.5	53.8
		4	3088.2	0.0	0.0	1300.2	1354.2	362.6	5.9	3.5	1.2	34.6
		5	3197.5	0.0	0.0	1301.1	1437.7	356.9	7.4	4.7	2.8	55.1
		1-5	15723.2	0.0	0.0	6624.2	7078.5	1621.0	30.6	19.6	10.5	213.9

Table C.4. HFT results (particle counts) for small chamber samples (12.5 to 19.0 mm [0.5 to 0.75 in]).

Aggregate Source	Source Type	Replicate Number	Particle Count Retained									
			0 Cycles	After 50 Cycles								
				Sieve Sizes								
			Total	25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Ashwill, Kingston	Gravel	1	623	0	0	77	372	171	4	4	4	11
		2	627	0	0	92	376	158	1	2	0	57
		3	620	0	0	80	395	143	3	4	8	37
		4	616	0	0	79	392	144	8	4	8	138
		5	616	0	0	75	388	151	2	2	0	33
		1-5	3102	0	0	403	1923	767	18	16	20	276
Big Springs, Harmony	Quarried	1	594	0	0	124	346	124	1	5	2	51
		2	615	0	0	134	327	154	0	1	4	30
		3	622	0	0	120	370	133	4	6	6	40
		4	629	0	0	113	353	164	1	4	5	22
		5	594	0	0	158	296	138	1	3	4	12
		1-5	3054	0	0	649	1692	713	7	19	21	155
Bryan Rock	Quarried	1	579	0	0	170	334	73	0	0	0	59
		2	559	0	0	139	341	88	0	0	0	0
		3	600	0	0	122	359	109	0	0	0	0
		4	587	0	0	126	342	119	0	0	0	0
		5	591	0	0	112	344	139	0	1	1	4
		1-5	2916	0	0	669	1720	528	0	1	1	63
Cedarville Plant	Quarried	1	636	0	0	85	324	226	2	1	0	9
		2	598	0	0	104	288	195	2	3	0	9
		3	587	0	0	101	326	159	3	1	0	9
		4	598	0	0	93	341	157	0	2	1	17
		5	604	0	0	92	319	192	3	1	1	4
		1-5	3023	0	0	475	1598	929	10	8	2	48

Table C.4. HFT results (particle counts) for small chamber samples (12.5 to 19.0 mm [0.5 to 0.75 in]) (continued).

Aggregate Source	Source Type	Replicate Number	Particle Count Retained									
			0 Cycles	After 50 Cycles								
				Sieve Sizes								
			Total	25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Early Chapel	Quarried	1	563	0	0	192	321	45	0	1	2	38
		2	569	0	0	135	338	97	1	6	0	16
		3	594	0	0	170	318	110	10	5	6	82
		4	497	0	0	163	271	66	0	0	0	21
		5	541	0	0	161	304	85	9	11	12	46
		1-5	2764	0	0	821	1552	403	20	23	20	203
Edward Kramer & Sons	Quarried	1	473	0	0	125	249	109	3	8	11	82
		2	497	0	0	112	258	127	3	2	4	72
		3*	488	0	0	131	248	100	4	4	7	33
		4	516	0	0	104	260	160	4	7	6	36
		5										
		1-5	1486	0	0	341	767	396	10	17	21	190
Goldberg, Rochester	Quarried	1	507	0	0	113	249	142	2	1	2	33
		2										
		3	541	0	0	117	187	137	4	2	2	23
		4	567	0	0	124	275	175	3	3	2	69
		5	519	0	0	114	264	146	1	8	6	42
		1-5	2134	0	0	468	975	600	10	14	12	167
Grand Meadow	Quarried	1	627	0	0	130	347	114	2	2	3	59
		2	667	0	0	88	413	166	1	1	0	5
		3	705	0	0	94	410	216	3	2	2	33
		4	672	0	0	92	405	173	3	0	2	6
		5	666	0	0	96	406	163	6	1	3	25
		1-5	3337	0	0	500	1981	832	15	6	10	128

Table C.4. HFT results (particle counts) for small chamber samples (12.5 to 19.0 mm [0.5 to 0.75 in]) (continued).

Aggregate Source	Source Type	Replicate Number	Particle Count Retained									
			Total	After 50 Cycles								
				Sieve Sizes								
				0 Cycles								
				25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Halma	Gravel	1	505	0	1	155	289	59	0	2	3	51
		2	464	0	0	162	268	34	4	3	7	27
		3	473	0	0	155	270	49	1	2	1	47
		4	492	0	0	150	280	62	2	0	1	23
		5	469	0	0	153	279	40	1	2	2	13
		1-5	1898	0	0	620	1097	185	8	7	11	110
Johnson, Henderson	Gravel	1	545	0	0	150	318	46	7	1	1	23
		2	606	0	0	121	373	112	1	4	4	10
		3	599	0	0	125	357	115	2	1	3	0
		4	607	0	0	121	368	121	6	5	3	62
		5	618	0	0	105	370	139	3	0	3	8.8
		1-5	2975	0	0	622	1786	533	19	11	14	103.8
Johnson, Le Sueur	Gravel	1	491	0	0	158	259	76	1	9	6	53
		2	478	0	0	131	279	64	3	10	11	168
		3	487	0	0	145	282	59	4	3	14	77
		4	486	0	0	156	270	62	3	4	11	96
		5	498	0	0	139	296	63	1	5	3	103
		1-5	2440	0	0	729	1386	324	12	31	45	497
Mark, Underwood	Gravel	1	462	0	0	157	240	55	2	4	1	38
		2	459	0	0	167	254	37	3	6	5	108
		3	465	0	0	153	264	47	0	4	4	136
		4	476	0	0	131	294	50	3	2	3	60
		5	535	0	0	103	348	85	0	2	3	27
		1-5	2397	0	0	711	1400	274	8	18	16	369

Table C.4. HFT results (particle counts) for small chamber samples (12.5 to 19.0 mm [0.5 to 0.75 in]) (continued).

Aggregate Source	Source Type	Replicate Number	Particle Count Retained									
			0 Cycles	After 50 Cycles								
				Sieve Sizes								
			Total	25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Northern Con, Luverne	Gravel	1	414	0	0	159	211	51	2	1	2	26
		2	479	0	0	119	294	67	10	8	6	26
		3	449	0	0	160	230	60	2	2	1	34
		4	453	0	0	190	215	48	5	6	3	44
		5	476	0	0	140	303	49	3	1	5	48
		1-5	2271	0	0	768	1253	275	22	18	17	178
North Star Kasota	Gravel	1	437	0	0	174	242	11	5	4	7	93
		2	536	0	0	149	333	56	3	3	7	32
		3	529	0	0	173	301	55	3	2	10	56
		4	486	0	0	149	294	48	2	0	1	45
		5	537	0	0	190	288	55	7	5	10	197
		1-5	2525	0	0	835	1458	225	20	14	35	423
Shiely Grey Cloud	Quarried	1	560	0	0	183	270	104	4	9	7	91
		2	498	0	0	180	239	81	0	0	0	12
		3	569	0	0	165	254	151	0	3	3	0
		4	508	0	0	181	201	125	1	1	1	9
		5	522	0	0	178	233	111	1	3	6	30
		1-5	2657	0	0	887	1197	572	6	16	17	142
SMC Mankato	Quarried	1	595	0	0	119	339	137	7	5	8	47
		2	582	0	0	125	327	129	9	15	16	39
		3	569	0	0	127	331	115	2	3	10	16
		4										
		5	586	0	0	110	345	129	4	15	12	111
		1-5	2332	0	0	481	1342	510	22	38	46	213

Table C.4. HFT results (particle counts) for small chamber samples (12.5 to 19.0 mm [0.5 to 0.75 in]) (continued).

Aggregate Source	Source Type	Replicate Number	Particle Count Retained									
			0 Cycles	After 50 Cycles								
				Sieve Sizes								
			Total	25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Swedberg	Quarried	1	351	0	0	173	214	67	7	8	11	160
		2	473	0	0	190	197	91	5	7	19	266
		3	462	0	0	187	208	75	2	4	9	66
		4	406	0	0	185	180	44	3	4	6	115
		5	400	0	0	172	250	78	4	8	10	25
		1-5	2092	0	0	907	1049	355	21	31	55	632
Ulland Northwood	Quarried	1	620	0	0	99	339	182	0	3	1	34
		2	598	0	0	111	317	168	5	10	4	42
		3	581	0	0	115	309	160	1	1	3	23
		4	524	0	0	114	277	131	3	1	5	30
		5	541	0	0	119	303	121	1	2	1	33
		1-5	2864	0	0	558	1545	762	10	17	14	162
Waterloo	Quarried	1	620	0	0	110	332	181	3	2	0	13
		2	614	0	0	120	356	140	3	1	3	46
		3	596	0	0	115	341	160	1	2	0	1
		4	575	0	0	124	325	125	0	0	0	16
		5	628	0	0	98	330	206	0	1	1	27
		1-5	3033	0	0	567	1684	812	7	6	4	103
Zumbrota	Quarried	1	527	0	0	165	261	103	4	3	8	51
		2	551	0	0	140	314	105	9	10	10	86
		3	517	0	0	165	286	79	2	7	5	26
		4	547	0	0	156	273	117	5	5	4	60
		5	547	0	0	149	292	114	7	7	14	90
		1-5	2689	0	0	775	1426	518	27	32	41	313

Table C.5. HFT results (normalized, mass retained) for small chamber samples (12.5 to 19 mm [0.5 in to 0.75 in]).

Aggregate Source	Source Type	Replicate Number	Normalized Mass Retained (%)								
			Sieve Size								
			25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Ashwill, Kingston	Gravel	1	0.000	0.000	19.759	61.135	18.258	0.230	0.094	0.026	0.249
		2	0.000	0.000	22.781	60.077	16.654	0.016	0.036	0.000	0.221
		3	0.000	0.000	20.484	63.903	14.866	0.087	0.068	0.061	0.465
		4	0.000	0.000	20.211	64.189	14.224	0.219	0.062	0.072	0.507
		5	0.000	0.000	18.997	64.233	15.453	0.080	0.037	0.000	0.383
		1-5	0.000	0.000	20.453	62.698	15.896	0.127	0.059	0.032	0.365
Big Springs, Harmony	Quarried	1	0.000	0.000	35.790	50.569	12.517	0.046	0.082	0.016	0.128
		2	0.000	0.000	35.961	48.347	14.891	0.000	0.019	0.038	0.407
		3	0.000	0.000	31.669	54.131	12.998	0.152	0.104	0.044	0.521
		4	0.000	0.000	30.351	52.287	15.904	0.065	0.071	0.048	0.740
		5	0.000	0.000	41.673	44.301	12.697	0.038	0.057	0.029	0.566
		1-5	0.000	0.000	35.095	49.923	13.799	0.060	0.067	0.035	0.474
Bryan Rock	Quarried	1	0.000	0.000	42.425	49.875	7.119	0.000	0.000	0.000	0.098
		2	0.000	0.000	36.935	53.274	8.964	0.000	0.000	0.000	0.370
		3	0.000	0.000	30.576	57.183	10.878	0.000	0.000	0.000	0.335
		4	0.000	0.000	32.690	54.070	12.538	0.000	0.000	0.000	0.295
		5	0.000	0.000	29.674	54.837	13.907	0.000	0.010	0.007	0.882
		1-5	0.000	0.000	34.493	53.830	10.672	0.000	0.002	0.001	0.391
Cedarville Plant	Quarried	1	0.000	0.000	24.751	50.378	24.134	0.142	0.023	0.000	0.194
		2	0.000	0.000	32.190	46.908	20.130	0.132	0.069	0.000	0.441
		3	0.000	0.000	29.810	52.682	16.650	0.160	0.016	0.000	0.358
		4	0.000	0.000	28.843	54.339	16.106	0.000	0.040	0.003	0.215
		5	0.000	0.000	27.686	50.873	20.336	0.130	0.010	0.010	0.515
		1-5	0.000	0.000	28.647	51.039	19.476	0.113	0.031	0.003	0.345

Table C.5. HFT results (normalized, mass retained) for small chamber samples (12.5 to 19 mm [0.5 in to 0.75 in]) (cont.).

Aggregate Source	Source Type	Replicate Number	Normalized Mass Retained (%)								
			Sieve Size								
			25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Early Chapel	Quarried	1	0.000	0.000	49.262	45.857	4.321	0.000	0.013	0.013	0.177
		2	0.000	0.000	35.583	53.321	10.085	0.038	0.094	0.000	0.549
		3	0.000	0.000	41.307	46.762	9.923	0.319	0.087	0.049	0.800
		4	0.000	0.000	46.736	45.123	7.202	0.000	0.000	0.000	0.491
		5	0.000	0.000	42.646	46.959	7.987	0.310	0.203	0.095	1.084
		1-5	0.000	0.000	43.027	47.617	7.950	0.139	0.081	0.032	0.627
Edward Kramer & Sons	Quarried	1	0.000	0.000	40.621	45.096	12.130	0.139	0.195	0.114	0.977
		2	0.000	0.000	35.198	47.996	14.677	0.165	0.029	0.050	1.036
		3*	0.000	0.000	42.180	44.434	10.801	0.183	0.072	0.069	1.229
		4	0.000	0.000	33.129	46.404	17.407	0.133	0.147	0.047	1.673
		5									
		1-5	0.000	0.000	36.328	46.495	14.731	0.145	0.124	0.070	1.228
Goldberg, Rochester	Quarried	1	0.000	0.000	36.853	44.849	15.672	0.108	0.018	0.025	1.089
		2									
		3	0.000	0.000	35.718	48.570	13.647	0.124	0.027	0.013	1.031
		4	0.000	0.000	37.670	42.904	17.119	0.094	0.054	0.017	1.388
		5	0.000	0.000	35.853	45.540	15.626	0.024	0.202	0.052	1.668
		1-5	0.000	0.000	36.523	45.477	15.511	0.088	0.075	0.027	1.294
Grand Meadow	Quarried	1	0.000	0.000	31.888	53.738	10.877	0.068	0.035	0.026	0.103
		2	0.000	0.000	22.678	59.900	16.266	0.023	0.029	0.000	0.395
		3	0.000	0.000	23.480	56.301	18.876	0.116	0.043	0.015	0.653
		4	0.000	0.000	22.772	58.879	17.046	0.070	0.000	0.022	0.483
		5	0.000	0.000	24.646	57.926	15.717	0.216	0.013	0.029	0.732
		1-5	0.000	0.000	25.077	57.335	15.791	0.098	0.024	0.019	0.474

Table C.5. HFT results (normalized, mass retained) for small chamber samples (12.5 to 19 mm [0.5 in to 0.75 in]) (cont.).

Aggregate Source	Source Type	Replicate Number	Normalized Mass Retained (%)								
			Sieve Size								
			25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Halma	Gravel	1	0.000	0.359	43.833	48.457	6.618	0.000	0.029	0.019	0.256
		2	0.000	0.000	46.967	48.157	4.175	0.083	0.046	0.036	0.337
		3	0.000	0.000	46.850	46.724	5.732	0.040	0.056	0.010	0.300
		4	0.000	0.000	43.954	48.168	7.256	0.075	0.000	0.007	0.223
		5	0.000	0.000	46.006	47.433	4.158	0.042	0.042	0.029	0.307
		1-5	0.000	0.000	45.940	47.620	5.325	0.060	0.036	0.020	0.292
Johnson, Henderson	Gravel	1	0.000	0.000	42.159	51.595	5.090	0.292	0.013	0.010	0.136
		2	0.000	0.000	32.166	56.460	10.459	0.039	0.072	0.021	0.309
		3	0.000	0.000	34.237	53.475	11.513	0.094	0.021	0.021	0.271
		4	0.000	0.000	31.001	56.339	11.638	0.150	0.075	0.033	0.414
		5	0.000	0.000	29.046	55.503	13.914	0.134	0.000	0.024	0.263
		1-5	0.000	0.000	33.548	54.740	10.631	0.139	0.037	0.022	0.281
Johnson, Le Sueur	Gravel	1	0.000	0.000	46.166	44.684	8.422	0.010	0.125	0.026	0.226
		2	0.000	0.000	41.480	49.937	7.165	0.106	0.189	0.083	0.596
		3	0.000	0.000	43.235	49.249	6.674	0.129	0.040	0.113	0.454
		4	0.000	0.000	44.788	47.830	6.406	0.058	0.049	0.052	0.416
		5	0.000	0.000	39.131	52.721	7.023	0.036	0.065	0.019	0.417
		1-5	0.000	0.000	42.955	48.890	7.137	0.067	0.093	0.058	0.421
Mark, Underwood	Gravel	1	0.000	0.000	50.089	42.889	6.331	0.101	0.052	0.013	0.094
		2	0.000	0.000	50.774	44.316	4.326	0.076	0.117	0.032	0.297
		3	0.000	0.000	48.296	45.803	5.156	0.000	0.068	0.032	0.363
		4	0.000	0.000	41.069	52.861	5.356	0.119	0.043	0.020	0.275
		5	0.000	0.000	31.310	58.961	9.146	0.000	0.030	0.030	0.204
		1-5	0.000	0.000	44.399	48.891	6.047	0.059	0.062	0.025	0.247

Table C.5. HFT results (normalized, mass retained) for small chamber samples (12.5 to 19 mm [0.5 in to 0.75 in]) (cont.).

Aggregate Source	Source Type	Replicate Number	Normalized Mass Retained (%)								
			Sieve Size								
			25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Northern Con, Luverne	Gravel	1	0.000	0.000	52.299	40.352	6.146	0.079	0.017	0.021	0.534
		2	0.000	0.000	38.746	52.278	7.244	0.411	0.110	0.048	0.432
		3	0.000	0.000	51.281	40.667	7.201	0.083	0.040	0.007	0.361
		4	0.000	0.000	57.866	35.486	4.879	0.196	0.106	0.035	0.513
		5	0.000	0.000	43.963	49.904	5.883	0.131	0.016	0.038	0.353
		1-5	0.000	0.000	48.899	43.693	6.253	0.179	0.058	0.030	0.438
North Star Kasota	Gravel	1	0.000	0.000	54.444	42.274	1.368	0.182	0.068	0.065	0.075
		2	0.000	0.000	42.677	51.433	5.371	0.109	0.054	0.060	0.266
		3	0.000	0.000	48.881	44.713	5.573	0.112	0.037	0.081	0.329
		4	0.000	0.000	44.926	49.031	5.097	0.073	0.000	0.006	0.332
		5	0.000	0.000	51.552	42.115	4.991	0.212	0.096	0.076	0.811
		1-5	0.000	0.000	48.489	45.874	4.536	0.138	0.052	0.059	0.373
Shiely Grey Cloud	Quarried	1	0.000	0.000	48.581	40.547	9.510	0.154	0.157	0.065	0.432
		2	0.000	0.000	52.486	37.989	7.964	0.000	0.000	0.003	0.867
		3	0.000	0.000	44.651	39.771	14.045	0.000	0.052	0.023	0.813
		4	0.000	0.000	51.486	33.540	12.660	0.030	0.017	0.010	1.442
		5	0.000	0.000	50.490	37.078	10.501	0.036	0.036	0.046	1.524
		1-5	0.000	0.000	49.519	37.811	10.933	0.044	0.053	0.030	1.013
SMC Mankato	Quarried	1	0.000	0.000	30.391	53.049	13.842	0.234	0.096	0.073	1.152
		2	0.000	0.000	32.069	52.088	12.383	0.306	0.244	0.119	1.779
		3	0.000	0.000	34.430	51.514	11.726	0.053	0.046	0.086	1.269
		4									
		5	0.000	0.000	28.311	55.324	12.813	0.182	0.218	0.069	1.778
		1-5	0.000	0.000	31.303	52.992	12.690	0.194	0.151	0.087	1.495

Table C.5. HFT results (normalized, mass retained) for small chamber samples (12.5 to 19 mm [0.5 in to 0.75 in]) (cont.).

Aggregate Source	Source Type	Replicate Number	Normalized Mass Retained (%)								
			Sieve Size								
			25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Swedberg	Quarried	1	0.000	0.000	53.006	38.288	6.982	0.220	0.178	0.124	0.487
		2	0.000	0.000	56.164	33.520	8.996	0.166	0.120	0.134	0.533
		3	0.000	0.000	56.104	35.555	7.312	0.071	0.071	0.104	0.547
		4	0.000	0.000	58.375	35.600	4.900	0.134	0.067	0.041	0.556
		5	0.000	0.000	50.057	41.857	6.880	0.123	0.117	0.096	0.511
		1-5	0.000	0.000	54.672	37.009	7.036	0.143	0.111	0.100	0.526
Ulland Northwood	Quarried	1	0.000	0.000	28.006	53.304	17.698	0.000	0.079	0.007	0.202
		2	0.000	0.000	31.454	50.547	16.684	0.197	0.171	0.039	0.496
		3	0.000	0.000	33.687	49.523	16.157	0.023	0.023	0.020	0.328
		4	0.000	0.000	34.381	49.953	14.496	0.118	0.018	0.043	0.519
		5	0.000	0.000	36.023	50.079	13.009	0.026	0.036	0.017	0.479
		1-5	0.000	0.000	32.685	50.690	15.628	0.072	0.066	0.025	0.403
Waterloo	Quarried	1	0.000	0.000	28.798	51.601	18.869	0.101	0.067	0.000	0.189
		2	0.000	0.000	31.767	53.858	13.511	0.091	0.016	0.026	0.391
		3	0.000	0.000	31.970	52.024	15.180	0.034	0.038	0.000	0.270
		4	0.000	0.000	34.904	51.075	13.342	0.000	0.000	0.000	0.235
		5	0.000	0.000	26.024	51.586	21.446	0.000	0.007	0.007	0.313
		1-5	0.000	0.000	30.675	52.042	16.474	0.046	0.025	0.007	0.280
Zumbrota	Quarried	1	0.000	0.000	45.146	41.794	11.203	0.174	0.048	0.076	0.884
		2	0.000	0.000	38.823	48.726	9.772	0.299	0.188	0.083	1.351
		3	0.000	0.000	43.909	45.756	7.669	0.077	0.128	0.048	1.716
		4	0.000	0.000	42.102	43.851	11.741	0.191	0.113	0.039	1.120
		5	0.000	0.000	40.691	44.963	11.162	0.231	0.147	0.088	1.723
		1-5	0.000	0.000	42.130	45.019	10.310	0.195	0.125	0.067	1.360

Table C.6. HFT results (normalized, particle counts) for small chamber samples (12.5 to 19 mm [0.5 in to 0.75 in]).

Aggregate Source	Source Type	Replicate Number	Normalized Particle Count Retained (%)								
			Sieve Size								
			25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Ashwill, Kingston	Gravel	1	0.000	0.000	12.360	59.711	27.448	0.642	0.642	0.642	1.766
		2	0.000	0.000	14.673	59.968	25.199	0.159	0.319	0.000	9.091
		3	0.000	0.000	12.903	63.710	23.065	0.484	0.645	1.290	5.968
		4	0.000	0.000	12.825	63.636	23.377	1.299	0.649	1.299	22.403
		5	0.000	0.000	12.175	62.987	24.513	0.325	0.325	0.000	5.357
		1-5	0.000	0.000	12.992	61.992	24.726	0.580	0.516	0.645	8.897
Big Springs, Harmony	Quarried	1	0.000	0.000	20.875	58.249	20.875	0.168	0.842	0.337	8.586
		2	0.000	0.000	21.789	53.171	25.041	0.000	0.163	0.650	4.878
		3	0.000	0.000	19.293	59.486	21.383	0.643	0.965	0.965	6.431
		4	0.000	0.000	17.965	56.121	26.073	0.159	0.636	0.795	3.498
		5	0.000	0.000	26.599	49.832	23.232	0.168	0.505	0.673	2.020
		1-5	0.000	0.000	21.251	55.403	23.346	0.229	0.622	0.688	5.075
Bryan Rock	Quarried	1	0.000	0.000	29.361	57.686	12.608	0.000	0.000	0.000	10.190
		2	0.000	0.000	24.866	61.002	15.742	0.000	0.000	0.000	0.000
		3	0.000	0.000	20.333	59.833	18.167	0.000	0.000	0.000	0.000
		4	0.000	0.000	21.465	58.262	20.273	0.000	0.000	0.000	0.000
		5	0.000	0.000	18.951	58.206	23.519	0.000	0.169	0.169	0.677
		1-5	0.000	0.000	22.942	58.985	18.107	0.000	0.034	0.034	2.160
Cedarville Plant	Quarried	1	0.000	0.000	13.365	50.943	35.535	0.314	0.157	0.000	1.415
		2	0.000	0.000	17.391	48.161	32.609	0.334	0.502	0.000	1.505
		3	0.000	0.000	17.206	55.537	27.087	0.511	0.170	0.000	1.533
		4	0.000	0.000	15.552	57.023	26.254	0.000	0.334	0.167	2.843
		5	0.000	0.000	15.232	52.815	31.788	0.497	0.166	0.166	0.662
		1-5	0.000	0.000	15.713	52.861	30.731	0.331	0.265	0.066	1.588

Table C.6. HFT results (normalized, particle counts) for small chamber samples (12.5 to 19 mm [0.5 in to 0.75 in])(cont.).

Aggregate Source	Source Type	Replicate Number	Normalized Particle Count Retained (%)								
			Sieve Size								
			25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Early Chapel	Quarried	1	0.000	0.000	34.103	57.016	7.993	0.000	0.178	0.355	6.750
		2	0.000	0.000	23.726	59.402	17.047	0.176	1.054	0.000	2.812
		3	0.000	0.000	28.620	53.535	18.519	1.684	0.842	1.010	13.805
		4	0.000	0.000	32.797	54.527	13.280	0.000	0.000	0.000	4.225
		5	0.000	0.000	29.760	56.192	15.712	1.664	2.033	2.218	8.503
		1-5	0.000	0.000	29.703	56.151	14.580	0.724	0.832	0.724	7.344
Edward Kramer & Sons	Quarried	1	0.000	0.000	26.427	52.643	23.044	0.634	1.691	2.326	17.336
		2	0.000	0.000	22.535	51.911	25.553	0.604	0.402	0.805	14.487
		3*	0.000	0.000	26.844	50.820	20.492	0.820	0.820	1.434	6.762
		4	0.000	0.000	20.155	50.388	31.008	0.775	1.357	1.163	6.977
		5									
		1-5	0.000	0.000	22.948	51.615	26.649	0.673	1.144	1.413	12.786
Goldberg, Rochester	Quarried	1	0.000	0.000	22.288	49.112	28.008	0.394	0.197	0.394	6.509
		2									
		3	0.000	0.000	21.627	34.566	25.323	0.739	0.370	0.370	4.251
		4	0.000	0.000	21.869	48.501	30.864	0.529	0.529	0.353	12.169
		5	0.000	0.000	21.965	50.867	28.131	0.193	1.541	1.156	8.092
		1-5	0.000	0.000	21.931	45.689	28.116	0.469	0.656	0.562	7.826
Grand Meadow	Quarried	1	0.000	0.000	20.734	55.343	18.182	0.319	0.319	0.478	9.410
		2	0.000	0.000	13.193	61.919	24.888	0.150	0.150	0.000	0.750
		3	0.000	0.000	13.333	58.156	30.638	0.426	0.284	0.284	4.681
		4	0.000	0.000	13.690	60.268	25.744	0.446	0.000	0.298	0.893
		5	0.000	0.000	14.414	60.961	24.474	0.901	0.150	0.450	3.754
		1-5	0.000	0.000	14.984	59.365	24.933	0.450	0.180	0.300	3.836

Table C.6. HFT results (normalized, particle counts) for small chamber samples (12.5 to 19 mm [0.5 in to 0.75 in])(cont.).

Aggregate Source	Source Type	Replicate Number	Normalized Particle Count Retained (%)								
			Sieve Size								
			25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Halma	Gravel	1	0.000	0.198	30.693	57.228	11.683	0.000	0.396	0.594	10.099
		2	0.000	0.000	34.914	57.759	7.328	0.862	0.647	1.509	5.819
		3	0.000	0.000	32.770	57.082	10.359	0.211	0.423	0.211	9.937
		4	0.000	0.000	30.488	56.911	12.602	0.407	0.000	0.203	4.675
		5	0.000	0.000	32.623	59.488	8.529	0.213	0.426	0.426	2.772
		1-5	0.000	0.000	32.666	57.798	9.747	0.421	0.369	0.580	5.796
Johnson, Henderson	Gravel	1	0.000	0.000	27.523	58.349	8.440	1.284	0.183	0.183	4.220
		2	0.000	0.000	19.967	61.551	18.482	0.165	0.660	0.660	1.650
		3	0.000	0.000	20.868	59.599	19.199	0.334	0.167	0.501	0.000
		4	0.000	0.000	19.934	60.626	19.934	0.988	0.824	0.494	10.214
		5	0.000	0.000	16.990	59.871	22.492	0.485	0.000	0.485	1.424
		1-5	0.000	0.000	20.908	60.034	17.916	0.639	0.370	0.471	3.489
Johnson, Le Sueur	Gravel	1	0.000	0.000	32.179	52.749	15.479	0.204	1.833	1.222	10.794
		2	0.000	0.000	27.406	58.368	13.389	0.628	2.092	2.301	35.146
		3	0.000	0.000	29.774	57.906	12.115	0.821	0.616	2.875	15.811
		4	0.000	0.000	32.099	55.556	12.757	0.617	0.823	2.263	19.753
		5	0.000	0.000	27.912	59.438	12.651	0.201	1.004	0.602	20.683
		1-5	0.000	0.000	29.877	56.803	13.279	0.492	1.270	1.844	20.369
Mark, Underwood	Gravel	1	0.000	0.000	33.983	51.948	11.905	0.433	0.866	0.216	8.225
		2	0.000	0.000	36.383	55.338	8.061	0.654	1.307	1.089	23.529
		3	0.000	0.000	32.903	56.774	10.108	0.000	0.860	0.860	29.247
		4	0.000	0.000	27.521	61.765	10.504	0.630	0.420	0.630	12.605
		5	0.000	0.000	19.252	65.047	15.888	0.000	0.374	0.561	5.047
		1-5	0.000	0.000	29.662	58.406	11.431	0.334	0.751	0.668	15.394

Table C.6. HFT results (normalized, particle counts) for small chamber samples (12.5 to 19 mm [0.5 in to 0.75 in])(cont.).

Aggregate Source	Source Type	Replicate Number	Normalized Particle Count Retained (%)								
			Sieve Size								
			25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Northern Con, Luverne	Gravel	1	0.000	0.000	38.406	50.966	12.319	0.483	0.242	0.483	6.280
		2	0.000	0.000	24.843	61.378	13.987	2.088	1.670	1.253	5.428
		3	0.000	0.000	35.635	51.225	13.363	0.445	0.445	0.223	7.572
		4	0.000	0.000	41.943	47.461	10.596	1.104	1.325	0.662	9.713
		5	0.000	0.000	29.412	63.655	10.294	0.630	0.210	1.050	10.084
		1-5	0.000	0.000	33.818	55.174	12.109	0.969	0.793	0.749	7.838
North Star Kasota	Gravel	1	0.000	0.000	39.817	55.378	2.517	1.144	0.915	1.602	21.281
		2	0.000	0.000	27.799	62.127	10.448	0.560	0.560	1.306	5.970
		3	0.000	0.000	32.703	56.900	10.397	0.567	0.378	1.890	10.586
		4	0.000	0.000	30.658	60.494	9.877	0.412	0.000	0.206	9.259
		5	0.000	0.000	35.382	53.631	10.242	1.304	0.931	1.862	36.685
		1-5	0.000	0.000	33.069	57.743	8.911	0.792	0.554	1.386	16.752
Shiely Grey Cloud	Quarried	1	0.000	0.000	32.679	48.214	18.571	0.714	1.607	1.250	16.250
		2	0.000	0.000	36.145	47.992	16.265	0.000	0.000	0.000	2.410
		3	0.000	0.000	28.998	44.640	26.538	0.000	0.527	0.527	0.000
		4	0.000	0.000	35.630	39.567	24.606	0.197	0.197	0.197	1.772
		5	0.000	0.000	34.100	44.636	21.264	0.192	0.575	1.149	5.747
		1-5	0.000	0.000	33.384	45.051	21.528	0.226	0.602	0.640	5.344
SMC Mankato	Quarried	1	0.000	0.000	20.000	56.975	23.025	1.176	0.840	1.345	7.899
		2	0.000	0.000	21.478	56.186	22.165	1.546	2.577	2.749	6.701
		3	0.000	0.000	22.320	58.172	20.211	0.351	0.527	1.757	2.812
		4									
		5	0.000	0.000	18.771	58.874	22.014	0.683	2.560	2.048	18.942
		1-5	0.000	0.000	20.626	57.547	21.870	0.943	1.630	1.973	9.134

Table C.6. HFT results (normalized, particle counts) for small chamber samples (12.5 to 19 mm [0.5 in to 0.75 in])(cont.).

Aggregate Source	Source Type	Replicate Number	Normalized Particle Count Retained (%)								
			Sieve Size								
			25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Swedberg	Quarried	1	0.000	0.000	49.288	60.969	19.088	1.994	2.279	3.134	45.584
		2	0.000	0.000	40.169	41.649	19.239	1.057	1.480	4.017	56.237
		3	0.000	0.000	40.476	45.022	16.234	0.433	0.866	1.948	14.286
		4	0.000	0.000	45.567	44.335	10.837	0.739	0.985	1.478	28.325
		5	0.000	0.000	43.000	62.500	19.500	1.000	2.000	2.500	6.250
		1-5	0.000	0.000	43.356	50.143	16.969	1.004	1.482	2.629	30.210
Ulland Northwood	Quarried	1	0.000	0.000	15.968	54.677	29.355	0.000	0.484	0.161	5.484
		2	0.000	0.000	18.562	53.010	28.094	0.836	1.672	0.669	7.023
		3	0.000	0.000	19.793	53.184	27.539	0.172	0.172	0.516	3.959
		4	0.000	0.000	21.756	52.863	25.000	0.573	0.191	0.954	5.725
		5	0.000	0.000	21.996	56.007	22.366	0.185	0.370	0.185	6.100
		1-5	0.000	0.000	19.483	53.946	26.606	0.349	0.594	0.489	5.656
Waterloo	Quarried	1	0.000	0.000	17.742	53.548	29.194	0.484	0.323	0.000	2.097
		2	0.000	0.000	19.544	57.980	22.801	0.489	0.163	0.489	7.492
		3	0.000	0.000	19.295	57.215	26.846	0.168	0.336	0.000	0.168
		4	0.000	0.000	21.565	56.522	21.739	0.000	0.000	0.000	2.783
		5	0.000	0.000	15.605	52.548	32.803	0.000	0.159	0.159	4.299
		1-5	0.000	0.000	18.694	55.523	26.772	0.231	0.198	0.132	3.396
Zumbrota	Quarried	1	0.000	0.000	31.309	49.526	19.545	0.759	0.569	1.518	9.677
		2	0.000	0.000	25.408	56.987	19.056	1.633	1.815	1.815	15.608
		3	0.000	0.000	31.915	55.319	15.280	0.387	1.354	0.967	5.029
		4	0.000	0.000	28.519	49.909	21.389	0.914	0.914	0.731	10.969
		5	0.000	0.000	27.239	53.382	20.841	1.280	1.280	2.559	16.453
		1-5	0.000	0.000	28.821	53.031	19.264	1.004	1.190	1.525	11.640

Table C.7. HFT results (mass retained) for small chamber samples (19.0 to 37.5 mm [0.75 to 1.5 in]).

Aggregate Source	Source Type	Replicate Number	Mass Retained (g)									
			0 Cycles	After 50 Cycles								
				Sieve Sizes								
			Total	25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Ashwill, Kingston	Gravel	1										
		2										
		3										
		4										
		5										
		1-5										
Big Springs, Harmony	Quarried	1	3087.5	1911.8	1039.6	108.0	0.0	7.2	1.3	3.1	0.7	11.1
		2	3158.9	2029.6	1068.4	33.5	3.4	1.4	0.0	1.0	0.4	9.8
		3	3047.4	2383.4	595.6	27.4	21.6	0.0	2.3	0.0	1.2	5.4
		4	3017.9	1593.6	1305.4	100.2	0.0	0.0	0.0	0.0	0.3	7.2
		5	3041.3	1841.6	997.7	155.1	0.0	11.8	1.4	4.5	1.1	15.0
		1-5	15353.0	9760.0	5006.7	424.2	25.0	20.4	5.0	8.6	3.7	48.5
Bryan Rock	Quarried	1	3024.9	1580.3	1214.8	200.7	3.9	5.7	1.9	2.2	1.2	9.3
		2	2992.7	1472.2	1366.7	124.9	4.0	0.0	0.0	3.7	1.0	10.0
		3	2953.2	1335.0	1440.5	199.4	8.0	0.0	0.0	1.1	0.0	8.1
		4	2389.8	687.4	1454.4	227.5	0.0	1.0	0.0	0.0	0.0	9.2
		5	3000.7	1353.2	1277.4	328.2	0.0	9.7	0.0	1.4	0.6	18.9
		1-5	14361.3	6428.1	6753.8	1080.7	15.9	16.4	1.9	8.4	2.8	55.5
Cedarville Plant	Quarried	1	3008.4	793.8	2112.8	81.2	5.1	0.0	0.0	1.0	0.0	7.8
		2	3079.9	902.1	2005.9	158.5	0.0	0.0	0.0	0.0	0.0	4.5
		3	3017.5	956.9	1877.6	162.2	6.2	2.7	0.0	0.0	0.1	4.5
		4										
		5	3056.4	734.0	2043.7	245.0	2.6	4.0	1.6	1.5	0.6	10.9
		1-5	12162.2	3386.8	8040.0	646.9	13.9	6.7	1.6	2.5	0.7	27.7

Table C.7. HFT results (mass retained) for small chamber samples (19.0 to 37.5 mm [0.75 to 1.5 in]) (cont.).

			Mass Retained (g)									
			0 Cycles	After 50 Cycles								
				Sieve Sizes								
Aggregate Source	Source Type	Replicate Number	Total	25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Early Chapel	Quarried	1	3027.8	206.5	2429.6	373.6	0.0	1.8	2.1	1.6	0.2	6.4
		2	3014.0	204.0	2417.8	348.9	7.3	0.0	1.5	0.5	0.8	16.8
		3	3046.8	106.4	2414.0	478.1	7.3	0.0	1.9	0.0	0.4	24.2
		4	2911.0	0.0	2322.6	548.6	0.0	1.6	0.0	0.6	0.0	19.3
		5	3013.0	203.7	2125.3	641.3	0.0	1.0	0.0	1.3	0.0	22.3
		1-5	15012.6	720.6	11709.3	2390.5	14.6	4.4	5.5	4.0	1.4	89.0
Edward Kramer & Sons	Quarried	1	2901.1	662.7	1885.4	269.6	25.0	0.0	2.6	1.7	1.4	23.3
		2	2785.0	1040.2	1449.8	245.6	6.9	2.3	1.3	0.9	0.6	22.5
		3	2889.2	1032.5	1659.3	147.4	3.1	0.9	0.2	0.0	0.7	25.7
		4	2888.4	1003.6	1436.4	392.0	6.3	0.0	0.0	1.5	1.1	31.1
		5	2916.0	1080.4	1211.7	566.4	0.0	3.4	0.0	1.4	0.3	34.1
		1-5	14379.7	4819.4	7642.6	1621.0	41.3	6.6	4.1	5.5	4.1	136.7
Goldberg, Rochester	Quarried	1	3007.6	1755.2	1071.5	119.4	28.9	4.9	1.3	2.7	0.6	13.9
		2	3005.8	1165.4	1702.8	104.1	0.0	5.1	1.3	3.4	0.8	10.6
		3	3011.4	1149.2	1753.5	78.2	0.0	0.0	0.0	0.6	0.2	16.8
		4	2804.1	1012.9	1353.7	394.3	0.0	3.6	0.0	0.3	0.6	26.5
		5	2992.3	788.7	1932.9	167.1	39.8	9.8	5.8	3.5	1.9	29.2
		1-5	14821.2	5871.4	7814.4	863.1	68.7	23.4	8.4	10.5	4.1	97.0
Grand Meadow	Quarried	1	3057.0	1064.4	1546.5	380.4	13.7	4.5	1.3	1.5	0.8	6.5
		2	3011.4	1268.5	1520.1	169.0	7.8	1.4	0.0	2.4	0.0	12.2
		3	2848.8	796.8	1665.7	346.4	0.0	8.9	0.8	0.6	0.5	16.3
		4	3081.8	694.4	1411.5	886.3	24.2	3.8	2.6	1.6	1.8	32.1
		5	3071.9	785.0	1653.0	594.5	0.0	3.3	0.0	2.3	0.0	14.5
		1-5	15070.9	4609.1	7796.8	2376.6	45.7	21.9	4.7	8.4	3.1	81.6

Table C.7. HFT results (mass retained) for small chamber samples (19.0 to 37.5 mm [0.75 to 1.5 in]) (cont.).

Aggregate Source	Source Type	Replicate Number	Mass Retained (g)									
			Total	0 Cycles								
				After 50 Cycles								
				Sieve Sizes								
				25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Halma	Gravel	1	3080.3	0.0	2770.3	290.2	0.0	0.0	0.0	0.0	0.0	5.3
		2	3092.5	0.0	2682.6	387.7	6.1	2.6	1.2	0.6	0.4	6.4
		3	3063.3	0.0	2708.2	338.4	0.0	1.9	0.0	0.0	0.0	7.6
		4	3050.7	0.0	2746.9	289.3	0.0	0.0	0.0	0.0	0.0	7.0
		5	3103.6	0.0	2711.0	366.7	5.8	3.1	0.0	0.4	0.2	10.3
		1-5	15390.4	0.0	13619.0	1672.3	11.9	7.6	1.2	1.0	0.6	36.6
Johnson, Henderson	Gravel	1	3116.2	1932.5	1105.2	61.2	7.6	0.0	0.0	0.0	0.0	5.1
		2	3088.5	1784.1	1224.6	22.8	0.0	12.7	8.3	8.5	3.3	25.4
		3	3104.2	1703.4	1304.9	69.8	8.1	2.3	0.0	0.0	0.0	6.7
		4	3118.4	1705.4	1340.1	44.8	4.5	4.1	0.0	0.0	0.3	9.2
		5	3097.8	1989.9	933.9	153.4	0.0	0.0	0.0	0.0	0.1	8.9
		1-5	15525.1	9115.3	5908.7	352.0	20.2	19.1	8.3	8.5	3.7	55.3
Johnson, Le Sueur	Gravel	1	3246.0	1120.2	2066.3	56.9	0.0	0.0	0.0	0.0	0.0	8.7
		2	3397.9	1125.4	2087.9	104.3	5.8	13.1	6.7	7.4	7.1	25.5
		3	3261.5	962.1	2161.1	80.4	0.0	2.4	0.9	0.2	1.0	35.4
		4	3213.6	994.9	2014.2	172.1	0.0	0.0	3.9	0.7	1.2	15.1
		5	3375.2	1103.8	1801.9	397.8	20.8	2.6	6.5	4.1	3.1	25.7
		1-5	16494.2	5306.4	10131.4	811.5	26.6	18.1	18.0	12.4	12.4	110.4
Mark, Underwood	Gravel	1	3104.9	1322.2	1580.2	215.9	0.0	0.0	0.0	0.0	0.0	2.1
		2	3135.7	1461.1	1609.6	53.8	0.0	2.1	0.0	0.5	0.0	3.7
		3	2991.7	700.7	2045.5	205.9	14.6	0.0	2.4	1.3	0.9	13.0
		4	3125.5	1091.2	1961.0	65.6	0.0	0.0	0.8	1.0	1.1	3.9
		5	3092.6	1005.2	1922.3	140.2	2.5	0.0	2.7	1.6	1.6	10.7
		1-5	15450.4	5580.4	9118.6	681.4	17.1	2.1	5.9	4.4	3.6	33.4

Table C.7. HFT results (mass retained) for small chamber samples (19.0 to 37.5 mm [0.75 to 1.5 in]) (cont.).

			Mass Retained (g)									
			0 Cycles	After 50 Cycles								
				Sieve Sizes								
Aggregate Source	Source Type	Replicate Number	Total	25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Northern Con, Luverne	Gravel	1	3094.6	1902.8	1083.0	86.8	15.7	3.7	0.0	0.0	0.0	3.2
		2	3048.0	2153.8	849.9	10.8	15.1	2.6	0.0	0.5	0.7	4.9
		3	3067.7	2152.3	858.3	9.9	5.0	2.2	0.0	0.0	0.0	5.8
		4	3114.7	2353.6	711.3	40.7	0.0	0.0	0.0	0.0	0.0	2.3
		5	3075.8	1739.9	1123.7	193.4	0.0	0.0	0.0	0.0	0.0	7.4
		1-5	15400.8	10302.4	4626.2	341.6	35.8	8.5	0.0	0.5	0.7	23.6
North Star Kasota	Gravel	1	3217.9	1825.0	1341.7	45.7	0.0	2.1	0.0	0.0	0.0	0.9
		2	3289.5	1031.1	2105.3	118.3	0.0	0.0	7.6	7.3	1.0	10.1
		3	3270.6	1279.1	1830.4	147.2	0.0	1.3	0.0	0.0	0.0	5.1
		4	3411.6	1008.4	2179.7	165.8	15.5	20.3	1.1	2.3	0.8	9.6
		5	3402.9	907.8	2326.1	126.5	12.4	3.5	2.1	2.4	3.0	12.5
		1-5	16592.5	6051.4	9783.2	603.5	27.9	27.2	10.8	12.0	4.8	38.2
Shiely Grey Cloud	Quarried	1	3038.4	1237.4	1589.7	175.3	12.3	3.4	0.0	0.6	0.2	8.2
		2	3039.3	924.6	1897.9	124.2	7.8	12.8	7.1	5.0	6.1	34.2
		3	3030.4	754.7	2054.9	166.5	7.4	4.8	1.0	1.3	0.7	31.8
		4	3067.5	1019.2	1730.9	264.8	6.4	0.0	0.8	1.7	0.5	23.1
		5	3056.0	882.5	1492.4	633.8	0.0	5.7	0.0	0.0	1.0	23.7
		1-5	15231.6	4818.4	8765.8	1364.6	33.9	26.7	8.9	8.6	8.5	121.0
SMC Mankato	Quarried	1	3059.2	2066.5	625.2	203.8	46.0	32.9	11.5	11.0	6.1	33.9
		2	3067.6	2157.0	678.7	89.4	43.2	34.1	5.9	8.3	6.2	29.8
		3	2668.4	1553.3	895.1	170.2	7.6	6.9	0.0	2.1	1.3	20.1
		4	2907.2	1822.8	794.3	228.8	5.1	9.6	1.2	3.5	1.2	21.7
		5	3019.9	1885.9	668.3	416.8	0.0	3.5	0.0	0.5	0.6	23.9
		1-5	14722.3	9485.5	3661.6	1109.0	101.9	87.0	18.6	25.4	15.4	129.4

Table C.7. HFT results (mass retained) for small chamber samples (19.0 to 37.5 mm [0.75 to 1.5 in]) (cont.).

			Mass Retained (g)									
			0 Cycles	After 50 Cycles								
				Sieve Sizes								
Aggregate Source	Source Type	Replicate Number	Total	25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Swedberg	Quarried	1	2961.3	743.7	1981.4	185.2	5.2	9.0	2.3	2.5	0.4	12.0
		2	3023.6	1012.3	1818.2	162.1	8.1	1.7	2.3	0.0	0.8	8.5
		3	2969.5	742.3	1967.3	187.6	13.7	4.9	7.1	4.7	1.5	12.3
		4	2962.8	899.4	1790.0	239.3	0.0	2.8	1.4	4.0	0.8	1.3
		5	3021.8	798.8	1680.5	515.7	0.0	1.7	0.9	2.7	0.1	12.1
		1-5	14939.0	4196.5	9237.4	1289.9	27.0	20.1	14.0	13.9	3.6	46.2
Ulland Northwood	Quarried	1	3047.2	1034.8	1522.8	438.9	21.5	3.4	0.0	0.3	0.0	8.5
		2	3063.1	999.7	1875.2	174.4	0.0	0.0	0.0	0.9	0.4	5.9
		3	3035.2	785.3	1998.0	236.1	0.0	0.0	0.0	0.5	0.0	5.6
		4	3051.8	1108.8	1804.5	116.3	6.3	0.0	0.0	0.0	0.7	7.0
		5	3075.6	793.3	1608.3	618.6	3.1	0.0	2.5	1.5	0.2	14.4
		1-5	15272.9	4721.9	8808.8	1584.3	30.9	3.4	2.5	3.2	1.3	41.4
Waterloo	Quarried	1	2915.4	0.0	2271.5	630.7	0.0	0.0	0.0	0.0	0.0	5.7
		2	2898.4	0.0	2157.4	723.2	0.0	0.0	0.0	0.7	0.1	7.2
		3										
		4	2806.4		1089.0	1691.0	0.0	0.0	0.0	0.0	0.0	13.6
		5										
		1-5	8620.2	0.0	5517.9	3044.9	0.0	0.0	0.0	0.7	0.1	26.5
Zumbrota	Quarried	1*	3023.2	1572.9	1250.4	100.0	10.6	19.2	4.1	9.8	5.1	6.9
		2	2963.3	1694.3	1175.5	35.2	5.2	7.5	0.0	1.2	0.3	28.7
		3	3006.4	1491.8	1295.8	34.9	20.5	17.1	5.0	5.5	3.9	38.5
		4	3007.9	1113.6	1639.8	159.8	18.9	5.6	1.0	1.0	1.1	41.4
		5	2992.5	871.3	1779.2	217.7	29.3	14.3	5.9	4.6	2.3	51.3
		1-5	11970.1	5171.0	5890.3	447.6	73.9	44.5	11.9	12.3	7.6	159.9

Table C.8. HFT results (particle counts) for small chamber samples (19.0 to 37.5 mm [0.75 to 1.5 in]).

			Particle Count Retained									
			0 Cycles	After 50 Cycles								
				Sieve Sizes								
Aggregate Source	Source Type	Replicate Number	Total	25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Ashwill, Kingston	Gravel	1										
		2										
		3										
		4										
		5										
		1-5										
Big Springs, Harmony	Quarried	1	109	41	58	11	0	4	2	6	4	125
		2	116	53	59	4	1	1	0	2	2	164
		3	82	48	30	3	4	0	2	0	3	36
		4	130	39	82	9	0	0	0	0	2	32
		5	99	40	49	14	0	5	1	7	4	60
		1-5	536	221	278	41	5	10	5	15	15	417
Bryan Rock	Quarried	1	133	41	75	19	1	3	2	4	2	134
		2	131	39	81	12	1	0	0	6	3	73
		3	136	34	86	16	2	0	0	1	0	43
		4	131	22	89	20	0	1	0	0	0	0
		5	133	31	71	32	0	5	0	2	3	38
		1-5	664	167	402	99	4	9	2	13	8	288
Cedarville Plant	Quarried	1	138	24	107	7	1	0	0	1	0	50
		2	152	27	110	14	0	0	0	0	0	0
		3	141	31	97	13	1	1	0	0	1	20
		4										
		5	83	23	110	21	1	2	2	3	2	10.9
		1-5	514	105	424	55	3	3	2	4	3	80.9

Table C.8. HFT results (particle counts) for small chamber samples (19.0 to 37.5 mm [0.75 to 1.5 in]) (cont.).

Aggregate Source	Source Type	Replicate Number	Particle Count Retained									
			0 Cycles	After 50 Cycles								
				Sieve Sizes								
				25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Early Chapel	Quarried	1	198	7	155	35	0	1	2	3	1	48
		2	197	7	156	33	1	0	1	1	2	14
		3	209	4	157	47	1	0	2	0	2	5
		4	206	0	152	54	0	1	0	1	0	17
		5	191	7	127	57	0	1	0	3	0	8
		1-5	803	18	592	191	2	2	3	5	4	44
Edward Kramer & Sons	Quarried	1	160	21	114	25	4	0	3	3	6	23.3
		2	136	30	90	23	2	1	2	2	3	63
		3	132	30	88	13	1	1	1	0	3	57
		4	144	31	79	35	2	0	0	4	4	40
		5	151	32	70	49	0	2	0	2	1	34
		1-5	723	144	441	145	9	4	6	11	17	217.3
Goldberg, Rochester	Quarried	1	117	48	57	10	4	1	1	4	2	93
		2	136	34	94	9	0	2	1	4	2	42
		3	129	32	92	6	0	0	0	1	1	14
		4	140	29	0	32	0	1	0	1	2	6
		5	150	21	112	16	7	5	4	6	8	56
		1-5	672	164	355	73	11	9	6	16	15	211
Grand Meadow	Quarried	1	167	30	103	38	3	2	1	3	4	96
		2	157	36	103	17	2	1	0	3	0	0
		3	166	22	108	36	0	4	1	1	2	23
		4	199	22	91	84	5	2	3	3	6	34
		5	188	23	107	57	0	1	0	3	0	79
		1-5	877	133	512	232	10	10	5	13	12	232

Table C.8. HFT results (particle counts) for small chamber samples (19.0 to 37.5 mm [0.75 to 1.5 in]) (cont.).

Aggregate Source	Source Type	Replicate Number	Particle Count Retained									
			0 Cycles	After 50 Cycles								
				Sieve Sizes								
			Total	25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Halma	Gravel	1	220	0	192	28	0	0	0	0	0	11
		2	224	0	188	35	1	1	1	1	1	13
		3	219	0	186	31	0	1	0	0	0	25
		4	212	0	187	25	0	0	0	0	0	6
		5	222		189	32	1	1	0	1	1	8
		1-5	1097	0	942	151	2	3	1	2	2	63
Johnson, Henderson	Gravel	1	108	51	53	5	1	0	0	0	0	71
		2	110	48	61	2	0	4	7	14	10	432
		3	109	41	60	6	2	1	0	0	0	29
		4	114	44	66	5	1	2	0	0	1	29
		5	106	48	46	14	0	0	0	0	1	2
		1-5	547	232	286	32	4	7	7	14	12	563
Johnson, Le Sueur	Gravel	1	145	30	112	5	0	0	0	0	0	27
		2	154	31	112	9	2	7	6	17	30	503
		3	149	24	116	8	0	1	2	1	6	650
		4	155	26	114	16	0	0	5	1	5	77
		5	160	30	95	34	4	1	6	7	12	234
		1-5	618	111	437	67	6	9	19	26	53	1464
Mark, Underwood	Gravel	1	125	30	79	17	0	0	0	0	0	17
		2	123	31	87	5	0	1	0	1	0	25
		3	167	17	126	21	3	0	3	2	3	64
		4	133	26	101	6	0	0	1	2	4	44
		5	145	22	111	12	1	0	2	3	6	88
		1-5	693	126	504	61	4	1	6	8	13	238

Table C.8. HFT results (particle counts) for small chamber samples (19.0 to 37.5 mm [0.75 to 1.5 in]) (cont.).

Aggregate Source	Source Type	Replicate Number	Particle Count Retained									
			Total	After 50 Cycles								
				Sieve Sizes								
				25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Northern Con, Luverne	Gravel	1	109	41	56	8	3	1	0	0	0	81
		2	97	49	46	1	3	1	0	1	3	7
		3	91	45	45	1	1	1	0	0	0	55
		4	78	43	32	3	0	0	0	0	0	95
		5	108	34	59	15	0	0	0	0	0	35
		1-5	483	212	238	28	7	3	0	1	3	273
North Star Kasota	Gravel	1	116	42	71	4	0	1	0	0	0	25
		2	153	27	116	9	0	0	8	12	5	166
		3	148	33	104	11	0	0	0	0	0	9
		4	170	26	127	15	3	7	1	4	5	65
		5	171	23	129	12	2	2	2	4	8	142
		1-5	758	151	547	51	5	10	11	20	18	407
Shiely Grey Cloud	Quarried	1	149	38	94	16	3	2	0	1	1	40
		2	155	27	115	12	2	6	7	9	25	141
		3	165	24	127	17	1	2	1	3	2	25
		4	165	32	109	23	2	0	1	2	2	11
		5	176	30	89	57	0	2	0	0	4	7
		1-5	810	151	534	125	8	12	9	15	34	224
SMC Mankato	Quarried	1	99	41	42	21	9	13	10	20	24	167
		2	93	43	45	10	8	15	6	15	23	295
		3	105	35	55	17	1	3	0	4	6	51
		4	114	38	54	24	1	4	1	6	5	56
		5	120	42	42	40	0	2	0	1	3	26
		1-5	531	199	238	112	19	37	17	46	61	595

Table C.8. HFT results (particle counts) for small chamber samples (19.0 to 37.5 mm [0.75 to 1.5 in]) (cont.).

			Particle Count Retained									
			0 Cycles	After 50 Cycles								
				Sieve Sizes								
Aggregate Source	Source Type	Replicate Number	Total	25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Swedberg	Quarried	1	169	21	130	17	2	4	3	4	2	244
		2	159	32	110	17	2	1	2	0	4	66
		3	175	23	133	19	3	3	6	11	10	87
		4	166	26	118	24	0	1	2	6	4	47
		5	178	24	104	50	0	1	1	5	1	81
		1-5	847	126	595	127	7	10	14	26	21	525
Ulland Northwood	Quarried	1	162	28	92	38	4	1	0	1	0	22
		2	152	24	112	16	0	0	0	1	1	0
		3	169	19	129	22	0	0	0	1	0	28
		4	147	27	109	11	1	0	0	0	3	34
		5	176	21	102	55	1	0	2	2	2	50
		1-5	806	119	544	142	6	1	2	5	6	134
Waterloo	Quarried	1	253	0	194	59	0	0	0	0	0	92
		2	252	0	182	67	0	0	0	2	1	16
		3										
		4	243	0	88	155	0	0	0	0	0	4
		5										
		1-5	748	0	464	281	0	0	0	2	1	112
Zumbrota	Quarried	1*	116	40	67	12	3	8	5	20	21	471
		2	103	41	61	4	1	2	0	2	1	62
		3	120	37	71	12	4	8	5	10	16	161
		4	146	31	101	16	4	2	1	1	6	75
		5	156	23	109	23	6	7	5	9	12	170
		1-5	525	132	342	55	15	19	11	22	35	468

Table C.9. HFT results (normalized, mass retained) for small chamber samples (19.0 to 37.5 mm [0.75 to 1.5 in])

Aggregate Source	Source Type	Replicate Number	Normalized Mass Retained (%)								
			Sieve Sizes								
			25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Ashwill, Kingston	Gravel	1									
		2									
		3									
		4									
		5									
		1-5									
Big Springs, Harmony	Quarried	1	61.921	33.671	3.498	0.000	0.233	0.042	0.100	0.023	0.360
		2	64.250	33.822	1.060	0.108	0.044	0.000	0.032	0.013	0.310
		3	78.211	19.545	0.899	0.709	0.000	0.075	0.000	0.039	0.177
		4	52.805	43.255	3.320	0.000	0.000	0.000	0.000	0.010	0.239
		5	60.553	32.805	5.100	0.000	0.388	0.046	0.148	0.036	0.493
		1-5	63.571	32.611	2.763	0.163	0.133	0.033	0.056	0.024	0.316
Bryan Rock	Quarried	1	52.243	40.160	6.635	0.129	0.188	0.063	0.073	0.040	0.307
		2	49.193	45.668	4.173	0.134	0.000	0.000	0.124	0.033	0.334
		3	45.205	48.778	6.752	0.271	0.000	0.000	0.037	0.000	0.274
		4	28.764	60.859	9.520	0.000	0.042	0.000	0.000	0.000	0.385
		5	45.096	42.570	10.937	0.000	0.323	0.000	0.047	0.020	0.630
		1-5	44.760	47.028	7.525	0.111	0.114	0.013	0.058	0.019	0.386
Cedarville Plant	Quarried	1	26.386	70.230	2.699	0.170	0.000	0.000	0.033	0.000	0.259
		2	29.290	65.129	5.146	0.000	0.000	0.000	0.000	0.000	0.146
		3	31.712	62.224	5.375	0.205	0.089	0.000	0.000	0.003	0.149
		4									
		5	24.015	66.866	8.016	0.085	0.131	0.052	0.049	0.020	0.357
		1-5	27.847	66.106	5.319	0.114	0.055	0.013	0.021	0.006	0.228

Table C.9. HFT results (normalized, mass retained) for small chamber samples (19.0 to 37.5 mm [0.75 to 1.5 in])(cont.)

Aggregate Source	Source Type	Replicate Number	Normalized Mass Retained (%)								
			Sieve Sizes								
			25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Early Chapel	Quarried	1	6.820	80.243	12.339	0.000	0.059	0.069	0.053	0.007	0.211
		2	6.768	80.219	11.576	0.242	0.000	0.050	0.017	0.027	0.557
		3	3.492	79.231	15.692	0.240	0.000	0.062	0.000	0.013	0.794
		4	0.000	79.787	18.846	0.000	0.055	0.000	0.021	0.000	0.663
		5	6.761	70.538	21.284	0.000	0.033	0.000	0.043	0.000	0.740
		1-5	4.800	77.996	15.923	0.097	0.029	0.037	0.027	0.009	0.593
Edward Kramer & Sons	Quarried	1	22.843	64.989	9.293	0.862	0.000	0.090	0.059	0.048	0.803
		2	37.350	52.057	8.819	0.248	0.083	0.047	0.032	0.022	0.808
		3	35.737	57.431	5.102	0.107	0.031	0.007	0.000	0.024	0.890
		4	34.746	49.730	13.572	0.218	0.000	0.000	0.052	0.038	1.077
		5	37.051	41.553	19.424	0.000	0.117	0.000	0.048	0.010	1.169
		1-5	33.515	53.149	11.273	0.287	0.046	0.029	0.038	0.029	0.951
Goldberg, Rochester	Quarried	1	58.359	35.626	3.970	0.961	0.163	0.043	0.090	0.020	0.462
		2	38.772	56.650	3.463	0.000	0.170	0.043	0.113	0.027	0.353
		3	38.162	58.229	2.597	0.000	0.000	0.000	0.020	0.007	0.558
		4	36.122	48.276	14.062	0.000	0.128	0.000	0.011	0.021	0.945
		5	26.358	64.596	5.584	1.330	0.328	0.194	0.117	0.063	0.976
		1-5	39.615	52.724	5.823	0.464	0.158	0.057	0.071	0.028	0.654
Grand Meadow	Quarried	1	34.818	50.589	12.444	0.448	0.147	0.043	0.049	0.026	0.213
		2	42.123	50.478	5.612	0.259	0.046	0.000	0.080	0.000	0.405
		3	27.970	58.470	12.160	0.000	0.312	0.028	0.021	0.018	0.572
		4	22.532	45.801	28.759	0.785	0.123	0.084	0.052	0.058	1.042
		5	25.554	53.810	19.353	0.000	0.107	0.000	0.075	0.000	0.472
		1-5	30.583	51.734	15.769	0.303	0.145	0.031	0.056	0.021	0.541

Table C.9. HFT results (normalized, mass retained) for small chamber samples (19.0 to 37.5 mm [0.75 to 1.5 in])(cont.)

Aggregate Source	Source Type	Replicate Number	Normalized Mass Retained (%)								
			Sieve Sizes								
			25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Halma	Gravel	1	0.000	89.936	9.421	0.000	0.000	0.000	0.000	0.000	0.172
		2	0.000	86.745	12.537	0.197	0.084	0.039	0.019	0.013	0.207
		3	0.000	88.408	11.047	0.000	0.062	0.000	0.000	0.000	0.248
		4	0.000	90.042	9.483	0.000	0.000	0.000	0.000	0.000	0.229
		5	0.000	87.350	11.815	0.187	0.100	0.000	0.013	0.006	0.332
		1-5	0.000	88.490	10.866	0.077	0.049	0.008	0.006	0.004	0.238
Johnson, Henderson	Gravel	1	62.015	35.466	1.964	0.244	0.000	0.000	0.000	0.000	0.164
		2	57.766	39.650	0.738	0.000	0.411	0.269	0.275	0.107	0.822
		3	54.874	42.037	2.249	0.261	0.074	0.000	0.000	0.000	0.216
		4	54.688	42.974	1.437	0.144	0.131	0.000	0.000	0.010	0.295
		5	64.236	30.147	4.952	0.000	0.000	0.000	0.000	0.003	0.287
		1-5	58.713	38.059	2.267	0.130	0.123	0.053	0.055	0.024	0.356
Johnson, Le Sueur	Gravel	1	34.510	63.657	1.753	0.000	0.000	0.000	0.000	0.000	0.268
		2	33.120	61.447	3.070	0.171	0.386	0.197	0.218	0.209	0.750
		3	29.499	66.261	2.465	0.000	0.074	0.028	0.006	0.031	1.085
		4	30.959	62.677	5.355	0.000	0.000	0.121	0.022	0.037	0.470
		5	32.703	53.386	11.786	0.616	0.077	0.193	0.121	0.092	0.761
		1-5	32.171	61.424	4.920	0.161	0.110	0.109	0.075	0.075	0.669
Mark, Underwood	Gravel	1	42.584	50.894	6.954	0.000	0.000	0.000	0.000	0.000	0.068
		2	46.596	51.331	1.716	0.000	0.067	0.000	0.016	0.000	0.118
		3	23.421	68.372	6.882	0.488	0.000	0.080	0.043	0.030	0.435
		4	34.913	62.742	2.099	0.000	0.000	0.026	0.032	0.035	0.125
		5	32.503	62.158	4.533	0.081	0.000	0.087	0.052	0.052	0.346
		1-5	36.118	59.019	4.410	0.111	0.014	0.038	0.028	0.023	0.216

Table C.9. HFT results (normalized, mass retained) for small chamber samples (19.0 to 37.5 mm [0.75 to 1.5 in])(cont.)

Aggregate Source	Source Type	Replicate Number	Normalized Mass Retained (%)								
			Sieve Sizes								
			25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Northern Con, Luverne	Gravel	1	61.488	34.996	2.805	0.507	0.120	0.000	0.000	0.000	0.103
		2	70.663	27.884	0.354	0.495	0.085	0.000	0.016	0.023	0.161
		3	70.160	27.979	0.323	0.163	0.072	0.000	0.000	0.000	0.189
		4	75.564	22.837	1.307	0.000	0.000	0.000	0.000	0.000	0.074
		5	56.567	36.534	6.288	0.000	0.000	0.000	0.000	0.000	0.241
		1-5	66.895	30.039	2.218	0.232	0.055	0.000	0.003	0.005	0.153
North Star Kasota	Gravel	1	56.714	41.695	1.420	0.000	0.065	0.000	0.000	0.000	0.028
		2	31.345	64.001	3.596	0.000	0.000	0.231	0.222	0.030	0.307
		3	39.109	55.965	4.501	0.000	0.040	0.000	0.000	0.000	0.156
		4	29.558	63.891	4.860	0.454	0.595	0.032	0.067	0.023	0.281
		5	26.677	68.356	3.717	0.364	0.103	0.062	0.071	0.088	0.367
		1-5	36.471	58.962	3.637	0.168	0.164	0.065	0.072	0.029	0.230
Shiely Grey Cloud	Quarried	1	40.725	52.320	5.769	0.405	0.112	0.000	0.020	0.007	0.270
		2	30.421	62.445	4.086	0.257	0.421	0.234	0.165	0.201	1.125
		3	24.904	67.810	5.494	0.244	0.158	0.033	0.043	0.023	1.049
		4	33.226	56.427	8.632	0.209	0.000	0.026	0.055	0.016	0.753
		5	28.878	48.835	20.740	0.000	0.187	0.000	0.000	0.033	0.776
		1-5	31.634	57.550	8.959	0.223	0.175	0.058	0.056	0.056	0.794
SMC Mankato	Quarried	1	67.550	20.437	6.662	1.504	1.075	0.376	0.360	0.199	1.108
		2	70.316	22.125	2.914	1.408	1.112	0.192	0.271	0.202	0.971
		3	58.211	33.544	6.378	0.285	0.259	0.000	0.079	0.049	0.753
		4	62.700	27.322	7.870	0.175	0.330	0.041	0.120	0.041	0.746
		5	62.449	22.130	13.802	0.000	0.116	0.000	0.017	0.020	0.791
		1-5	64.429	24.871	7.533	0.692	0.591	0.126	0.173	0.105	0.879

Table C.9. HFT results (normalized, mass retained) for small chamber samples (19.0 to 37.5 mm [0.75 to 1.5 in])(cont.)

Aggregate Source	Source Type	Replicate Number	Normalized Mass Retained (%)								
			Sieve Sizes								
			25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Swedberg	Quarried	1	25.114	66.910	6.254	0.176	0.304	0.078	0.084	0.014	0.405
		2	33.480	60.134	5.361	0.268	0.056	0.076	0.000	0.026	0.281
		3	24.997	66.250	6.318	0.461	0.165	0.239	0.158	0.051	0.414
		4	30.356	60.416	8.077	0.000	0.095	0.047	0.135	0.027	0.044
		5	26.435	55.613	17.066	0.000	0.056	0.030	0.089	0.003	0.400
		1-5	28.091	61.834	8.634	0.181	0.135	0.094	0.093	0.024	0.309
Ulland Northwood	Quarried	1	33.959	49.974	14.403	0.706	0.112	0.000	0.010	0.000	0.279
		2	32.637	61.219	5.694	0.000	0.000	0.000	0.029	0.013	0.193
		3	25.873	65.828	7.779	0.000	0.000	0.000	0.016	0.000	0.185
		4	36.333	59.129	3.811	0.206	0.000	0.000	0.000	0.023	0.229
		5	25.793	52.292	20.113	0.101	0.000	0.081	0.049	0.007	0.468
		1-5	30.917	57.676	10.373	0.202	0.022	0.016	0.021	0.009	0.271
Waterloo	Quarried	1	0.000	77.914	21.633	0.000	0.000	0.000	0.000	0.000	0.196
		2	0.000	74.434	24.952	0.000	0.000	0.000	0.024	0.003	0.248
		3									
		4	0.000	38.804	60.255	0.000	0.000	0.000	0.000	0.000	0.485
		5									
		1-5	0.000	64.011	35.323	0.000	0.000	0.000	0.008	0.001	0.307
Zumbrota	Quarried	1*	52.028	41.360	3.308	0.351	0.635	0.136	0.324	0.169	0.228
		2	57.176	39.669	1.188	0.175	0.253	0.000	0.040	0.010	0.969
		3	49.621	43.101	1.161	0.682	0.569	0.166	0.183	0.130	1.281
		4	37.023	54.516	5.313	0.628	0.186	0.033	0.033	0.037	1.376
		5	29.116	59.455	7.275	0.979	0.478	0.197	0.154	0.077	1.714
		1-5	43.199	49.208	3.739	0.617	0.372	0.099	0.103	0.063	1.336

Table C.10. HFT results (normalized, particle counts) for small chamber samples (19.0 to 37.5 mm [0.75 to 1.5 in]).

Aggregate Source	Source Type	Replicate Number	Normalized Particle Count Retained (%)								
			Sieve Sizes								
			25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Ashwill, Kingston	Gravel	1									
		2									
		3									
		4									
		5									
		1-5									
Big Springs, Harmony	Quarried	1	37.615	53.211	10.092	0.000	3.670	1.835	5.505	3.670	114.679
		2	45.690	50.862	3.448	0.862	0.862	0.000	1.724	1.724	141.379
		3	58.537	36.585	3.659	4.878	0.000	2.439	0.000	3.659	43.902
		4	30.000	63.077	6.923	0.000	0.000	0.000	0.000	1.538	24.615
		5	40.404	49.495	14.141	0.000	5.051	1.010	7.071	4.040	60.606
		1-5	41.231	51.866	7.649	0.933	1.866	0.933	2.799	2.799	77.799
Bryan Rock	Quarried	1	30.827	56.391	14.286	0.752	2.256	1.504	3.008	1.504	100.752
		2	29.771	61.832	9.160	0.763	0.000	0.000	4.580	2.290	55.725
		3	25.000	63.235	11.765	1.471	0.000	0.000	0.735	0.000	31.618
		4	16.794	67.939	15.267	0.000	0.763	0.000	0.000	0.000	0.000
		5	23.308	53.383	24.060	0.000	3.759	0.000	1.504	2.256	28.571
		1-5	25.151	60.542	14.910	0.602	1.355	0.301	1.958	1.205	43.373
Cedarville Plant	Quarried	1	17.391	77.536	5.072	0.725	0.000	0.000	0.725	0.000	36.232
		2	17.763	72.368	9.211	0.000	0.000	0.000	0.000	0.000	0.000
		3	21.986	68.794	9.220	0.709	0.709	0.000	0.000	0.709	14.184
		4									
		5	27.711	132.530	25.301	1.205	2.410	2.410	3.614	2.410	13.133
		1-5	20.428	82.490	10.700	0.584	0.584	0.389	0.778	0.584	15.739

Table C.10. HFT results (normalized, particle counts) for small chamber samples (19.0 to 37.5 mm [0.75 to 1.5 in]) (cont.).

Aggregate Source	Source Type	Replicate Number	Normalized Particle Count Retained (%)								
			Sieve Sizes								
			25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Early Chapel	Quarried	1	3.535	78.283	17.677	0.000	0.505	1.010	1.515	0.505	24.242
		2	3.553	79.188	16.751	0.508	0.000	0.508	0.508	1.015	7.107
		3	1.914	75.120	22.488	0.478	0.000	0.957	0.000	0.957	2.392
		4	0.000	73.786	26.214	0.000	0.485	0.000	0.485	0.000	8.252
		5	3.665	66.492	29.843	0.000	0.524	0.000	1.571	0.000	4.188
		1-5	2.242	73.724	23.786	0.249	0.249	0.374	0.623	0.498	5.479
Edward Kramer & Sons	Quarried	1	13.125	71.250	15.625	2.500	0.000	1.875	1.875	3.750	14.563
		2	22.059	66.176	16.912	1.471	0.735	1.471	1.471	2.206	46.324
		3	22.727	66.667	9.848	0.758	0.758	0.758	0.000	2.273	43.182
		4	21.528	54.861	24.306	1.389	0.000	0.000	2.778	2.778	27.778
		5	21.192	46.358	32.450	0.000	1.325	0.000	1.325	0.662	22.517
		1-5	19.917	60.996	20.055	1.245	0.553	0.830	1.521	2.351	30.055
Goldberg, Rochester	Quarried	1	41.026	48.718	8.547	3.419	0.855	0.855	3.419	1.709	79.487
		2	25.000	69.118	6.618	0.000	1.471	0.735	2.941	1.471	30.882
		3	24.806	71.318	4.651	0.000	0.000	0.000	0.775	0.775	10.853
		4	20.714	0.000	22.857	0.000	0.714	0.000	0.714	1.429	4.286
		5	14.000	74.667	10.667	4.667	3.333	2.667	4.000	5.333	37.333
		1-5	24.405	52.827	10.863	1.637	1.339	0.893	2.381	2.232	31.399
Grand Meadow	Quarried	1	17.964	61.677	22.754	1.796	1.198	0.599	1.796	2.395	57.485
		2	22.930	65.605	10.828	1.274	0.637	0.000	1.911	0.000	0.000
		3	13.253	65.060	21.687	0.000	2.410	0.602	0.602	1.205	13.855
		4	11.055	45.729	42.211	2.513	1.005	1.508	1.508	3.015	17.085
		5	12.234	56.915	30.319	0.000	0.532	0.000	1.596	0.000	42.021
		1-5	15.165	58.381	26.454	1.140	1.140	0.570	1.482	1.368	26.454

Table C.10. HFT results (normalized, particle counts) for small chamber samples (19.0 to 37.5 mm [0.75 to 1.5 in]) (cont.).

Aggregate Source	Source Type	Replicate Number	Normalized Particle Count Retained (%)								
			Sieve Sizes								
			25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Halma	Gravel	1	0.000	87.273	12.727	0.000	0.000	0.000	0.000	0.000	5.000
		2	0.000	83.929	15.625	0.446	0.446	0.446	0.446	0.446	5.804
		3	0.000	84.932	14.155	0.000	0.457	0.000	0.000	0.000	11.416
		4	0.000	88.208	11.792	0.000	0.000	0.000	0.000	0.000	2.830
		5	0.000	85.135	14.414	0.450	0.450	0.000	0.450	0.450	3.604
		1-5	0.000	85.871	13.765	0.182	0.273	0.091	0.182	0.182	5.743
Johnson, Henderson	Gravel	1	47.222	49.074	4.630	0.926	0.000	0.000	0.000	0.000	65.741
		2	43.636	55.455	1.818	0.000	3.636	6.364	12.727	9.091	392.727
		3	37.615	55.046	5.505	1.835	0.917	0.000	0.000	0.000	26.606
		4	38.596	57.895	4.386	0.877	1.754	0.000	0.000	0.877	25.439
		5	45.283	43.396	13.208	0.000	0.000	0.000	0.000	0.943	1.887
		1-5	42.413	52.285	5.850	0.731	1.280	1.280	2.559	2.194	102.925
Johnson, Le Sueur	Gravel	1	20.690	77.241	3.448	0.000	0.000	0.000	0.000	0.000	18.621
		2	20.130	72.727	5.844	1.299	4.545	3.896	11.039	19.481	326.623
		3	16.107	77.852	5.369	0.000	0.671	1.342	0.671	4.027	436.242
		4	16.774	73.548	10.323	0.000	0.000	3.226	0.645	3.226	49.677
		5	18.750	59.375	21.250	2.500	0.625	3.750	4.375	7.500	146.250
		1-5	17.961	70.712	10.841	0.971	1.456	3.074	4.207	8.576	236.893
Mark, Underwood	Gravel	1	24.000	63.200	13.600	0.000	0.000	0.000	0.000	0.000	13.600
		2	25.203	70.732	4.065	0.000	0.813	0.000	0.813	0.000	20.325
		3	10.180	75.449	12.575	1.796	0.000	1.796	1.198	1.796	38.323
		4	19.549	75.940	4.511	0.000	0.000	0.752	1.504	3.008	33.083
		5	15.172	76.552	8.276	0.690	0.000	1.379	2.069	4.138	60.690
		1-5	18.182	72.727	8.802	0.577	0.144	0.866	1.154	1.876	34.343

Table C.10. HFT results (normalized, particle counts) for small chamber samples (19.0 to 37.5 mm [0.75 to 1.5 in]) (cont.).

Aggregate Source	Source Type	Replicate Number	Normalized Particle Count Retained (%)								
			Sieve Sizes								
			25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Northern Con, Luverne	Gravel	1	37.615	51.376	7.339	2.752	0.917	0.000	0.000	0.000	74.312
		2	50.515	47.423	1.031	3.093	1.031	0.000	1.031	3.093	7.216
		3	49.451	49.451	1.099	1.099	1.099	0.000	0.000	0.000	60.440
		4	55.128	41.026	3.846	0.000	0.000	0.000	0.000	0.000	121.795
		5	31.481	54.630	13.889	0.000	0.000	0.000	0.000	0.000	32.407
		1-5	43.892	49.275	5.797	1.449	0.621	0.000	0.207	0.621	56.522
North Star Kasota	Gravel	1	36.207	61.207	3.448	0.000	0.862	0.000	0.000	0.000	21.552
		2	17.647	75.817	5.882	0.000	0.000	5.229	7.843	3.268	108.497
		3	22.297	70.270	7.432	0.000	0.000	0.000	0.000	0.000	6.081
		4	15.294	74.706	8.824	1.765	4.118	0.588	2.353	2.941	38.235
		5	13.450	75.439	7.018	1.170	1.170	1.170	2.339	4.678	83.041
		1-5	19.921	72.164	6.728	0.660	1.319	1.451	2.639	2.375	53.694
Shiely Grey Cloud	Quarried	1	25.503	63.087	10.738	2.013	1.342	0.000	0.671	0.671	26.846
		2	17.419	74.194	7.742	1.290	3.871	4.516	5.806	16.129	90.968
		3	14.545	76.970	10.303	0.606	1.212	0.606	1.818	1.212	15.152
		4	19.394	66.061	13.939	1.212	0.000	0.606	1.212	1.212	6.667
		5	17.045	50.568	32.386	0.000	1.136	0.000	0.000	2.273	3.977
		1-5	18.642	65.926	15.432	0.988	1.481	1.111	1.852	4.198	27.654
SMC Mankato	Quarried	1	41.414	42.424	21.212	9.091	13.131	10.101	20.202	24.242	168.687
		2	46.237	48.387	10.753	8.602	16.129	6.452	16.129	24.731	317.204
		3	33.333	52.381	16.190	0.952	2.857	0.000	3.810	5.714	48.571
		4	33.333	47.368	21.053	0.877	3.509	0.877	5.263	4.386	49.123
		5	35.000	35.000	33.333	0.000	1.667	0.000	0.833	2.500	21.667
		1-5	37.476	44.821	21.092	3.578	6.968	3.202	8.663	11.488	112.053

Table C.10. HFT results (normalized, particle counts) for small chamber samples (19.0 to 37.5 mm [0.75 to 1.5 in]) (cont.).

Aggregate Source	Source Type	Replicate Number	Normalized Particle Count Retained (%)								
			Sieve Sizes								
			25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Swedberg	Quarried	1	12.426	76.923	10.059	1.183	2.367	1.775	2.367	1.183	144.379
		2	20.126	69.182	10.692	1.258	0.629	1.258	0.000	2.516	41.509
		3	13.143	76.000	10.857	1.714	1.714	3.429	6.286	5.714	49.714
		4	15.663	71.084	14.458	0.000	0.602	1.205	3.614	2.410	28.313
		5	13.483	58.427	28.090	0.000	0.562	0.562	2.809	0.562	45.506
		1-5	14.876	70.248	14.994	0.826	1.181	1.653	3.070	2.479	61.983
Ulland Northwood	Quarried	1	17.284	56.790	23.457	2.469	0.617	0.000	0.617	0.000	13.580
		2	15.789	73.684	10.526	0.000	0.000	0.000	0.658	0.658	0.000
		3	11.243	76.331	13.018	0.000	0.000	0.000	0.592	0.000	16.568
		4	18.367	74.150	7.483	0.680	0.000	0.000	0.000	2.041	23.129
		5	11.932	57.955	31.250	0.568	0.000	1.136	1.136	1.136	28.409
		1-5	14.764	67.494	17.618	0.744	0.124	0.248	0.620	0.744	16.625
Waterloo	Quarried	1	0.000	76.680	23.320	0.000	0.000	0.000	0.000	0.000	36.364
		2	0.000	72.222	26.587	0.000	0.000	0.000	0.794	0.397	6.349
		3									
		4	0.000	36.214	63.786	0.000	0.000	0.000	0.000	0.000	1.646
		5									
		1-5	0.000	62.032	37.567	0.000	0.000	0.000	0.267	0.134	14.973
Zumbrota	Quarried	1*	34.483	57.759	10.345	2.586	6.897	4.310	17.241	18.103	406.034
		2	39.806	59.223	3.883	0.971	1.942	0.000	1.942	0.971	60.194
		3	30.833	59.167	10.000	3.333	6.667	4.167	8.333	13.333	134.167
		4	21.233	69.178	10.959	2.740	1.370	0.685	0.685	4.110	51.370
		5	14.744	69.872	14.744	3.846	4.487	3.205	5.769	7.692	108.974
		1-5	25.143	65.143	10.476	2.857	3.619	2.095	4.190	6.667	89.143

APPENDIX D

Hydraulic Fracture Test Results – Large Chamber

Table D.1. HFT results (mass retained) for large chamber samples (19.0 to 37.5 mm [0.75 to 1.5 in])

			Mass Retained (g)									
			0 Cycles	After 50 Cycles								
				Sieve Sizes								
Aggregate Source	Source Type	Replicate Number	Total	25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Johnson, Henderson	Gravel	1	15220.2	8499.7	6287.1	253.7	12.9	0.0	0.0	0.0	1.9	101.9
		2	15007.9	8006.6	6641.6	208.5	5.2	0.9	0.0	0.0	7.1	94.9
		3	14986.8	7131.6	7493.2	189.2	0.0	1.7	0.0	0.0	4.6	90.3
		1-3	45214.9	23637.9	20421.9	651.4	18.1	2.6	0.0	0.0	13.6	287.1
Edward Kramer and Sons	Quarried	1	15144.3	4165.7	9183.8	1202.2	80.2	38.6	0.0	0.0	31.3	279.1
		2	15496.3	4005.9	9461.9	1454.6	89.4	32.3	0.0	0.0	35.1	264.7
		3	14824.1	4689.7	8344.7	1224.0	92.4	31.3	0.0	0.0	27.6	264.8
		1-3	45464.7	12861.3	26990.4	3880.8	262.0	102.2	0.0	0.0	94.0	808.6
North Star Kasota	Gravel	1	15261.4	5150.0	9663.7	346.6	0.0	4.4	0.0	0.0	1.4	73.6
		2	15112.9	5239.4	9199.0	526.2	27.6	0.0	0.0	0.0	6.2	59.3
		3	15173.1	5575.2	9217.8	248.1	8.4	4.5	0.0	0.0	2.3	63.7
		1-3	45547.4	15964.6	28080.5	1120.9	36.0	8.9	0.0	0.0	9.9	196.6
Early Chapel	Quarried	1	14802.3	592.5	12309.8	1564.7	2.3	6.5	0.0	0.0	9.2	218.0
		2	14806.9	903.7	11774.3	1774.0	12.7	10.1	0.0	0.0	13.2	238.9
		3	14874.8	708.9	11945.7	1883.4	29.9	7.7	0.0	0.0	7.3	226.0
		1-3	44484.0	2205.1	36029.8	5222.1	44.9	24.3	0.0	0.0	29.7	682.9

Table D.2. HFT results (particle counts) for large chamber samples (19.0 to 37.5 mm [0.75 to 1.5 in])

			Particle Count Retained									
			0 Cycles	After 50 Cycles								
				Sieve Sizes								
Aggregate Source	Source Type	Replicate Number	Total	25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Johnson, Henderson	Gravel	1	570	218	328	25	2	0	0	0	6	34
		2	577	210	351	20	1	1	0	0	12	0
		3	597	184	294	18	0	1	0	0	8	0
		1-3	1744	612	973	63	3	2	0	0	26	34
Edward Kramer and Sons	Quarried	1	794	127	541	117	18	18	0	0	76	0
		2	806	118	555	135	18	16	0	0	67	0
		3	777	142	509	122	19	14	0	0	68	57
		1-3	2377	387	1605	374	55	48	0	0	211	57
North Star Kasota	Gravel	1	719	134	554	31	0	2	0	0	4	0
		2	715	132	532	47	6	0	0	0	13	0
		3	688	145	518	24	1	2	0	0	6	0
		1-3	2122	411	1604	102	7	4	0	0	23	0
Early Chapel	Quarried	1	978	23	814	147	1	3	0	0	17	20
		2	960	37	765	166	2	5	0	0	30	0
		3	981	27	777	173	6	4	0	0	13	0
		1-3	2919	87	2356	486	9	12	0	0	60	20

Table D.3. HFT results (mass retained, normalized) for large chamber samples (19.0 to 37.5 mm [0.75 to 1.5 in])

Aggregate Source	Source Type	Replicate Number	Normalized Mass Retained (%)								
			Sieve Sizes								
			25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Johnson, Henderson	Gravel	1	55.8449	41.3076	1.6669	0.0848	0.0000	0.0000	0.0000	0.0125	0.6695
		2	53.3492	44.2540	1.3893	0.0346	0.0060	0.0000	0.0000	0.0473	0.6323
		3	47.5859	49.9987	1.2624	0.0000	0.0113	0.0000	0.0000	0.0307	0.6025
		1-3	52.2790	45.1663	1.4407	0.0400	0.0058	0.0000	0.0000	0.0301	0.6350
Edward Kramer and Sons	Quarried	1	27.5067	60.6420	7.9383	0.5296	0.2549	0.0000	0.0000	0.2067	1.8429
		2	25.8507	61.0591	9.3868	0.5769	0.2084	0.0000	0.0000	0.2265	1.7081
		3	31.6356	56.2914	8.2568	0.6233	0.2111	0.0000	0.0000	0.1862	1.7863
		1-3	28.2885	59.3656	8.5359	0.5763	0.2248	0.0000	0.0000	0.2068	1.7785
North Star Kasota	Gravel	1	33.7453	63.3212	2.2711	0.0000	0.0288	0.0000	0.0000	0.0092	0.4823
		2	34.6684	60.8685	3.4818	0.1826	0.0000	0.0000	0.0000	0.0410	0.3924
		3	36.7440	60.7509	1.6351	0.0554	0.0297	0.0000	0.0000	0.0152	0.4198
		1-3	35.0505	61.6512	2.4610	0.0790	0.0195	0.0000	0.0000	0.0217	0.4316
Early Chapel	Quarried	1	4.0028	83.1614	10.5707	0.0155	0.0439	0.0000	0.0000	0.0622	1.4727
		2	6.1032	79.5190	11.9809	0.0858	0.0682	0.0000	0.0000	0.0891	1.6134
		3	4.7658	80.3083	12.6617	0.2010	0.0518	0.0000	0.0000	0.0491	1.5193
		1-3	4.9571	80.9950	11.7393	0.1009	0.0546	0.0000	0.0000	0.0668	1.5352

Table D.4. HFT results (particle counts, normalized) for large chamber samples (19.0 to 37.5 mm [0.75 to 1.5 in])

Aggregate Source	Source Type	Replicate Number	Normalized Particle Count Retained (%)								
			Sieve Sizes								
			25.0 mm (1 in)	19.0 mm (0.75 in)	16.0 mm (0.625 in)	12.5 mm (0.5 in)	9.50 mm (0.375 in)	8.00 mm (0.3125 in)	6.35 mm (0.25 in)	4.75 mm (#4)	Pan
Johnson, Henderson	Gravel	1	38.2456	57.5439	4.3860	0.3509	0.0000	0.0000	0.0000	1.0526	5.9649
		2	36.3951	60.8319	3.4662	0.1733	0.1733	0.0000	0.0000	2.0797	0.0000
		3	30.8208	49.2462	3.0151	0.0000	0.1675	0.0000	0.0000	1.3400	0.0000
		1-3	35.0917	55.7913	3.6124	0.1720	0.1147	0.0000	0.0000	1.4908	1.9495
Edward Kramer and Sons	Quarried	1	15.9950	68.1360	14.7355	2.2670	2.2670	0.0000	0.0000	9.5718	0.0000
		2	14.6402	68.8586	16.7494	2.2333	1.9851	0.0000	0.0000	8.3127	0.0000
		3	18.2754	65.5084	15.7014	2.4453	1.8018	0.0000	0.0000	8.7516	7.3359
		1-3	16.2810	67.5221	15.7341	2.3138	2.0194	0.0000	0.0000	8.8767	2.3980
North Star Kasota	Gravel	1	18.6370	77.0515	4.3115	0.0000	0.2782	0.0000	0.0000	0.5563	0.0000
		2	18.4615	74.4056	6.5734	0.8392	0.0000	0.0000	0.0000	1.8182	0.0000
		3	21.0756	75.2907	3.4884	0.1453	0.2907	0.0000	0.0000	0.8721	0.0000
		1-3	19.3685	75.5891	4.8068	0.3299	0.1885	0.0000	0.0000	1.0839	0.0000
Early Chapel	Quarried	1	2.3517	83.2311	15.0307	0.1022	0.3067	0.0000	0.0000	1.7382	2.0450
		2	3.8542	79.6875	17.2917	0.2083	0.5208	0.0000	0.0000	3.1250	0.0000
		3	2.7523	79.2049	17.6351	0.6116	0.4077	0.0000	0.0000	1.3252	0.0000
		1-3	2.9805	80.7126	16.6495	0.3083	0.4111	0.0000	0.0000	2.0555	0.6852

APPENDIX E

Development of Regression Models

APPENDIX E

DEVELOPMENT OF REGRESSION MODELS

E.1 Introduction

The small chamber hydraulic fracture test results were modeled using the computer software package called *ARC* developed at the University of Minnesota Department of Applied Statistics. Cook and Weisberg discuss the use of this software package in reference (9).

Separate models were developed for each initial size fraction using the cumulative percentage of mass or particles passing each screen as the predictors for the response variables “percent dilation per 100 cycles of freezing and thawing” and “durability factor,” which are described in section 4.1 “Concrete Properties.” Table E.1 presents a summary of the regression models developed under this study.

Table E.1. Regression analysis matrix.

Explanatory Variables (Cumulative Percentage Passing)	Response Variable	Initial Size Fraction
Mass	Percent Dilation per 100 Cycles	4.75 to 12.5 mm
	Durability Factor	
Particle Counts	Percent Dilation per 100 Cycles	12.5 to 19.0 mm
	Durability Factor	
Mass	Percent Dilation per 100 Cycles	19.0 to 37.5 mm
	Durability Factor	
Particle Counts	Percent Dilation per 100 Cycles	19.0 to 37.5 mm
	Durability Factor	
Mass	Percent Dilation per 100 Cycles	19.0 to 37.5 mm
	Durability Factor	

The following subsections describe the development of the models generated for each size fraction and the selection of the final model in each category.

E.2 Initial Size Fraction: 4.75 to 12.5 mm (#4 to 0.5 in)

Hydraulic fracture testing on the initial size fraction 4.75 to 12.5 mm (#4 to 0.5 in) was performed according to the procedure outlined in appendix A. The percentage of mass retained (POMR) on the specified sieves for each sample (replicate) and the average percentage of original mass retained (APOMR) were computed for each source using the equations presented in section 3.5.3. Table C.1 of appendix C presents the actual masses retained on the specified sieves at 0 and 50 cycles for each replicate test sample of each source. The normalized data (i.e., POMR and APOMR) are presented in table C.2 of appendix C.

E.2.1 Mass Retained Data

E.2.1.1 Explanatory Variables

As stated previously, models were developed to predict both percent dilation per 100 cycles of rapid freezing and thawing (dil) and durability factor (DF). The following predictors were initially selected as the independent or explanatory variables for these models:

38M:	Percentage of mass passing the 9.50 mm (0.375 in) screen.
516M:	Percentage of mass passing the 8.00 mm (0.3125 in) screen.
14M:	Percentage of mass passing the 6.35 mm (0.25 in) screen.
4M:	Percentage of mass passing the 4.75 mm (#4) screen.
C:	Carbonate content of the source, percent.

The percentage of mass passing each specified screen was calculated as described below using the APOMR data presented in table C.2.

□ Total Percentage of Original Mass Retained [TPOMR]:

$$\text{TPOMR} = \sum_{i=1}^n \text{APOMR}_i = 100\%* \quad (\text{Eqn. E.1})$$

where: APOMR_i = average percentage of original mass retained on screen i and

n = total number of screens.

*Use a TPOMR of 100 percent. Mass losses due to screening operations are accounted for in equations E.6 and E.7.

- Percentage of mass passing the 9.50 mm (0.375 in) screen [38M]:

$$38M = TPOMR - APOMR_{38} \quad (\text{Eqn. E.2})$$

where: TPOMR = Total percentage of original mass retained and

APOMR₃₈ = average percentage of original mass retained on the 9.50 mm (0.375 in) screen.

- Percentage of mass passing the 8.00 mm (0.3125 in) screen [516M]:

$$516M = 38M - APOMR_{516} \quad (\text{Eqn. E.3})$$

where: 38M = Percentage of mass passing the 9.50 mm (0.375 in) screen and

APOMR₅₁₆ = average percentage of original mass retained on the 8.00 mm (0.3125 in) screen.

- Percentage of mass passing the 6.35 mm (0.25 in) screen [14M]:

$$14M = 516M - APOMR_{14} \quad (\text{Eqn. E.4})$$

where: 516M = Percentage of mass passing the 8.00 mm (0.3125 in) screen and

APOMR₁₄ = average percentage of original mass retained on the 6.35 mm (0.25 in) screen.

- Percentage of mass passing the 4.75 mm (#4) screen [4_{actual}]:

$$4_{\text{actual}} = 14M - APOMR_4 \quad (\text{Eqn. E.5})$$

where: 14M = Percentage of mass passing the 6.35 mm (0.25 in) screen and

APOMR₄ = average percentage of original mass retained on the 4.75 mm (#4) screen.

- Percentage of mass lost due to testing [M_{loss}]:

$$M_{\text{loss}} = 4_{\text{actual}} - APOMR_{\text{pan}} \quad (\text{Eqn. E.6})$$

where: 4_{actual} = Percentage of mass passing the 4.75 mm (#4) screen and

APOMR_{pan} = average percentage of original mass retained on the pan.

- Percentage of mass passing the 4.75 mm (#4) screen (adjusted for mass loss during testing) [4M]:

$$4M = 4_{\text{actual}} - M_{\text{loss}} \quad (\text{Eqn. E.7})$$

□ Percentage of mass passing the pan [pan]:

$$\text{Pan} = 4M - \text{APOMR}_{\text{pan}} = 0 \quad (\text{Eqn. E.8})$$

The predictors defined by equations E.2 – E.4 and E.7 were calculated for each of 20 sources tested and were then transferred as an *lsp* file into *ARC*. Equation E.8 was used as a check to make sure that there were no computational errors.

It should be noted that as much as one percent of the mass of a given test sample was sometimes lost during testing. As a result, the total percentage of original material mass retained during the final sieve analyses was sometimes reduced to 99 percent or more. Because of the great care taken during testing, it was assumed that the material lost during testing was probably very fine and would have passed the 4.75 mm (#4) sieve. Equations E.5 – E.7 were developed to account for this mass loss and attribute it to the proper particle size in the regression analysis.

E.2.1.2 Transformations to Normality

Two-dimensional scatter plots were developed to show the conditional distribution of the response variables (dilation/100 cycles and durability factor) to changes in each explanatory variable. The scatter plot matrix for the previously defined explanatory and response variables is presented in figure E.1. Normality is achieved when the mean functions are linear and the variance functions are constant (9). Figure E.1 shows that there is little normality between the response and explanatory variables in the inverse fitted value plots (marginal distribution plots).

Normality can sometimes be achieved or improved through transformations of the explanatory variables. In this study, explanatory variable transformations were performed using the Box-Cox method (a numerical procedure) in an attempt to improve the linearity of the relationships. Figure E.2 presents the scatter plot matrix for the transformed explanatory variables and shows that the Box-Cox transformations were not effective in producing linear relationships between the percentage of particles passing the designated screens and either percent dilation or the durability factor.

Even though normality was apparently not achieved, nonlinear and multiple linear regression analyses were performed on this data set, as described in subsections E2.1.3 and E2.1.4.

Figure E.1. Scatter plot matrix for responses and explanatory variables (percentage of mass passing, 4.75 to 12.5 mm [#4 to 0.5 in]).

E.2.1.3 Nonlinear Regression

Previous studies have shown that concrete freeze-thaw durability is often a function of carbonate content. Therefore, the following general form was adopted for both models:

$$E(y|x) = C * (\text{linear combination of } 38M, 516M, 14M \text{ and } 4M)$$

therefore,

$$E(y|x) = C * (\alpha + \beta_1 * 38M + \beta_2 * 516M + \beta_3 * 14M + \beta_4 * 4M) \quad (\text{Eqn. E.9})$$

Figure E.2. Scatter plot matrix for responses and transformed explanatory variables (percentage of mass passing, 4.75 to 12.5 mm [#4 to 0.5 in]).

Regression analyses were performed using both the untransformed (identity) and transformed explanatory variables. Tables E.2 and E.3 present the results of regression analyses for the untransformed and transformed explanatory variables, respectively, including the parameter estimates, Wald statistics, degrees of freedom, number of observations (n), coefficient of multiple determination (R^2), standard deviation about the least squares line ($\hat{\sigma}$), adjusted R^2 and a subsection presenting the model expressions.

Table E.2. Nonlinear regression models using untransformed data
(percentage of mass passing, 4.75 to 12.5 mm [#4 to 0.5 in]).

Parameter	Estimate (Wald Test) [p-value]	
	Model Number	
	N1 (% Dil/100 cycles)	N2 (DF)
α	0.00103401 (1.340) [0.1803]	0.550572 (0.539) [0.5897]
38M	-0.0000102810 (-0.271) [0.7866]	-0.0185399 (-0.369) [0.7120]
516M	-0.0000223007 (-0.357) [0.7215]	0.0861688 (1.041) [0.2977]
14M	0.0000538035 (0.840) [0.4010]	-0.120840 (-1.426) [0.1538]
4M	-0.0000412558 (-0.252) [0.8008]	0.0162062 (0.075) [0.9403]
Df	15	15
N	20	20
r^2	0.5753	0.7224
$\hat{\sigma}$	0.0352171	46.5824
r^2_{adj}	0.424	0.623
${}^{N1,N2} Y=C*(\alpha+\beta_1*38M+\beta_2*516M+\beta_3*14M+\beta_4*4M)$		

The Wald statistic is used to perform a significance test for each parameter (i.e., to test the hypotheses $H_0: \beta = 0$). This statistic divides a parameter estimate by its standard error and then squares it (10).

The coefficient of multiple determination, interpreted as the proportion of variation in observed y values that is explained by the fitted model, is defined as follows (11):

Table E.3. Nonlinear regression models using transformed data (percentage of mass passing, 4.75 to 12.5 mm [#4 to 0.5 in]).

Parameter	Estimate (Wald Test) [p-value]					
	Model Number					
	N3 (% dil/100 cycles)	N4 (DF)	N5 (% dil/100 cycles)	N6 (DF)	N7 (% dil/100 cycles)	N8 (DF)
α	8.070412E-6 (1.037) [0.2997]	-0.000825088 (-0.058) [0.9538]	2.228873E-6 (1.269) [0.2046]	0.00160539 (0.541) [0.5888]	0.00371456 (1.069) [0.2850]	-0.471868 (-0.094) [0.9250]
β_1	-2.005917E-9 (-1.962) [0.0498]	1.296718E-6 (0.693) [0.4884]	-1.307060E-8 (-0.141) [0.8882]	-0.0000854055 (-0.543) [0.5868]	-8.468595E-7 (-1.811) [0.0702]	0.000492543 (0.730) [0.4654]
β_2	2.638897E-7 (1.334) [0.1823]	-0.0000590968 (-0.163) [0.8704]	-7.864361E-8 (-0.457) [0.6479]	0.000298937 (1.027) [0.3043]	0.000110288 (1.274) [0.2026]	-0.0243830 (-0.195) [0.8452]
β_3	-2.900323E-6 (-0.721) [0.4706]	-0.00122456 (-0.166) [0.8678]	1.587959E-7 (0.868) [0.3852]	-0.000383144 (-1.240) [0.2151]	-0.00126279 (-0.737) [0.4613]	-0.368799 (-0.149) [0.8814]
β_4	-2.992015E-6 (-0.934) [0.3503]	0.00246889 (0.421) [0.6737]	-1.351930E-7 (-0.361) [0.7179]	0.0000900020 (0.142) [0.8868]	-0.00144596 (-0.997) [0.3187]	1.11655 (0.534) [0.5936]
Df	15	15	15	15	15	15
N	20	20	20	20	20	20
r^2	0.5753	0.5450	0.5848	0.5569	0.6187	0.7035
$\hat{\sigma}$	0.0325792	59.6342	0.0348194	58.85	0.0333705	48.145
r^2_{adj}	0.424	0.383	0.437	0.399	0.482	0.598
N3,N4 $Y=C^{2.33}*(\alpha+\beta_1*38M^2+\beta_2*516M+\beta_3*14M^{0.31}+\beta_4*4M^{-0.25})$						
N5,N6 $Y=C^{2.33}*(\alpha+\beta_1*38M+\beta_2*516M+\beta_3*14M+\beta_4*4M)$						
N7,N8 $Y=C*(\alpha+\beta_1*38M^2+\beta_2*516M+\beta_3*14M^{0.31}+\beta_4*4M^{-0.25})$						

$$R^2 = 1 - (SS_{\text{Resid}} / SS_{\text{Total}}) \quad (\text{Eqn. E.10})$$

where: SS_{Resid} = residual (or error) sum of squares, and
 SS_{Total} = total sum of squares.

Additionally, an estimate of the random deviation variance ($\hat{\sigma}^2$) is expressed by (11):

$$\hat{\sigma}^2 = SS_{\text{Resid}} / (n - k + 1) \quad (\text{Eqn. E.11})$$

where: SS_{Resid} = residual (or error) sum of squares,
 n = number of observations, and
 k = number of predictors.

A desirable model is generally considered to be one with a high R^2 and low $\hat{\sigma}^2$. These conditions can often be achieved by adding predictors to the model, regardless of whether the additional variables are statistically significant. Thus, it is possible to have models that yield large values of R^2 , but are poor predictors of new observations or of the mean function.

The parameter R^2 can be adjusted to account for the numbers of predictors and observations used to develop any given model. This “adjusted R^2 ” is calculated as follows (11):

$$\text{Adjusted } R^2 = 1 - \frac{n - 1}{n - (k + 1)} \cdot \frac{SS_{\text{Resid}}}{SS_{\text{Total}}} \quad (\text{Eqn. E.12})$$

Where: SS_{Resid} = residual (or error) sum of squares,
 SS_{Total} = total sum of squares,
 n = number of observations, and
 k = number of predictors.

A reasonable strategy in model selection is to identify the model with the largest value of adjusted R^2 (typically a model using fewer than the total number of predictors available) and

then to consider only that model and any others whose adjusted R^2 values are nearly as large (11).

Figures E.3 through E.6 present 2-dimensional plots of actual versus predicted response variable values for the models produced using the untransformed and transformed data sets, respectively. As illustrated in figures E.3 through E.6, models N1 – N8 do a poor job of accurately modeling the data. Therefore, further regression analyses were performed to determine whether a better model of freeze-thaw test results might be developed as a function of the cumulative percentage of mass passing each designated sieve.

E.2.1.4 Multiple Linear Regression

Equation E.9 was modified slightly for multiple linear regression using both the transformed and untransformed data. The following general model forms were adopted for use:

$$E(y|x) = \alpha + \beta_1 * C * 38M + \beta_2 * C * 516M + \beta_3 * C * 14M + \beta_4 * C * 4M \quad (\text{Eqn. E.13})$$

$$E(y|x) = \alpha + \beta_1 * 38M + \beta_2 * 516M + \beta_3 * 14M + \beta_4 * 4M \quad (\text{Eqn. E.14})$$

Numerous linear regression models were formulated based on the above two *base* equations; however, only the model with the best adjusted R^2 was recorded in tables E.4 and E.5 for the response variables percent dilation (model L1) and durability factor (model L2), respectively. As in the nonlinear regression tables, these tables contain a list of the parameter estimates, degrees of freedom, number of observations (n), coefficient of determination (R^2), standard deviation about the least squares line ($\hat{\sigma}$), adjusted R^2 , a subsection presenting the model expression, and the t-statistics, which is used in place of the Wald statistic in multiple linear regression.

Tables E.4 and E.5 also contain the modeling information resulting from stepwise regression, addition of main-effects terms, performed on the models. Again, from this subset of models, the model containing the largest adjusted R^2 was chosen for further analysis. Therefore, from the set

a. Model N1.

b. Model N2.

Figure E.3. Actual versus predicted rapid freezing and thawing test results for models N1 and N2 (untransformed data, percentage of mass passing, 4.75 to 12.5 mm [#4 to 0.5 in])

a. Model N3.

b. Model N4.

Figure E.4. Actual versus predicted rapid freezing and thawing test results for models N3 and N4 (transformed data, percentage of mass passing, 4.75 to 12.5 mm [#4 to 0.5 in]).

a. Model N5.

b. Model N6.

Figure E.5. Actual versus predicted rapid freezing and thawing test results for models N5 and N6 (transformed data, percentage of mass passing, 4.75 to 12.5 mm [#4 to 0.5 in]).

a. Model N7.

b. Model N8.

Figure E.6. Actual versus predicted rapid freezing and thawing test results for models N7 and N8 (transformed data, percentage of mass passing, 4.75 to 12.5 mm [#4 to 0.5 in]).

Table E.4. Multiple linear regression models for response variable “percent dilation per 100 cycles” (percentage of mass passing, 4.75 to 12.5 mm [#4 to 0.5 in]).

Variable	Estimates (t-value) [p-value]				
	Model Number				
	L1	L1A	L1B	L1C	L1D
Constant	0.00341740 (0.221) [0.8281]	0.0221772 (0.232) [0.8201]	0.0951994 (0.443) [0.6648]	0.217903 (0.752) [0.4667]	0.312224 (0.806) [0.4372]
$C^{2.33} \cdot 38M^2$	-1.346140E-9 (-1.622) [0.1256]	-1.378032E-9 (-1.579) [0.1366]	-1.534070E-9 (-1.552) [0.1447]	-1.773046E-9 (-1.648) [0.1254]	-9.505134E-10 (-0.396) [0.7000]
$C^{2.33} \cdot 516M$	9.199502E-8 (0.793) [0.4402]	1.021024E-7 (0.784) [0.4462]	1.434840E-7 (0.832) [0.4205]	1.484940E-7 (0.841) [0.4169]	4.011051E-8 (0.120) [0.9068]
$C^{2.33} \cdot 14M^{0.31}$	1.084382E-6 (0.811) [0.4303]	8.446276E-7 (0.460) [0.6523]	3.994725E-7 (0.180) [0.8601]	6.739372E-7 (0.292) [0.7756]	1.365622E-6 (0.456) [0.6570]
$C^{2.33} \cdot 4M^{-0.25}$	9.663262E-8 (0.091) [0.9284]	3.580062E-7 (0.209) [0.8371]	4.559344E-7 (0.256) [0.8021]	5.769563E-7 (0.315) [0.7583]	2.552498E-9 (0.001) [0.9992]
$4M^{-0.25}$		-0.0179345 (-0.199) [0.8453]	-0.0475858 (-0.393) [0.7007]	-0.105374 (-0.691) [0.5029]	-0.118252 (-0.731) [0.4800]
$14M^{0.31}$			-0.0205449 (-0.383) [0.7080]	-0.0870829 (-0.749) [0.4684]	-0.162111 (-0.709) [0.4929]
516M				0.00216516 (0.649) [0.5285]	0.00882893 (0.502) [0.6255]
$38M^2$					-0.0000438370 (-0.387) [0.7064]
Df	15	14	13	12	11
N	20	20	20	20	20
r^2	0.372418	0.374185	0.381164	0.402152	0.410165
$\hat{\sigma}$	0.0336723	0.034805	0.0359169	0.0367441	0.0381199
r^2_{adj}	0.205	0.151	0.096	0.053	-0.019
L1	$Y = \alpha + C^{2.33} \cdot (\beta_1 \cdot 38M^2 + \beta_2 \cdot 516M + \beta_3 \cdot 14M^{0.31} + \beta_4 \cdot 4M^{-0.25})$				
L1A	$Y = \alpha + C^{2.33} \cdot (\beta_1 \cdot 38M^2 + \beta_2 \cdot 516M + \beta_3 \cdot 14M^{0.31} + \beta_4 \cdot 4M^{-0.25}) + \beta_5 \cdot 4M^{-0.25}$				
L1B	$Y = \alpha + C^{2.33} \cdot (\beta_1 \cdot 38M^2 + \beta_2 \cdot 516M + \beta_3 \cdot 14M^{0.31} + \beta_4 \cdot 4M^{-0.25}) + \beta_5 \cdot 4M^{-0.25} + \beta_6 \cdot 14M^{0.31}$				
L1C	$Y = \alpha + C^{2.33} \cdot (\beta_1 \cdot 38M^2 + \beta_2 \cdot 516M + \beta_3 \cdot 14M^{0.31} + \beta_4 \cdot 4M^{-0.25}) + \beta_5 \cdot 4M^{-0.25} + \beta_6 \cdot 14M^{0.31} + \beta_7 \cdot 516M$				
L1D	$Y = \alpha + C^{2.33} \cdot (\beta_1 \cdot 38M^2 + \beta_2 \cdot 516M + \beta_3 \cdot 14M^{0.31} + \beta_4 \cdot 4M^{-0.25}) + \beta_5 \cdot 4M^{-0.25} + \beta_6 \cdot 14M^{0.31} + \beta_7 \cdot 516M + \beta_8 \cdot 38M^2$				

Table E.5. Multiple linear regression models for response variable “durability factor”
(percentage of mass passing, 4.75 to 12.5 mm [#4 to 0.5 in]).

Variable	Estimates (t-value) [p-value]				
	Model Number				
	L2	L2A	L2B	L2C	L2D
Constant	93.5617 (7.245) [0.0000]	78.2013 (0.979) [0.3444]	46.4641 (0.258) [0.8004]	-74.1006 (-0.307) [0.7642]	-154.416 (-0.479) [0.6414]
$C^{2.33*38M^2}$	1.312434E-6 (1.894) [0.0777]	1.338547E-6 (1.837) [0.0876]	1.406365E-6 (1.697) [0.1135]	1.641175E-6 (1.831) [0.0921]	9.407716E-7 (0.470) [0.6474]
$C^{2.33*516M}$	-0.000111392 (-1.150) [0.2683]	-0.000119667 (-1.100) [0.2898]	-0.000137653 (-0.952) [0.3586]	-0.000142575 (-0.969) [0.3516]	-0.0000502847 (-0.180) [0.8602]
$C^{2.33*14M^{0.31}}$	-0.000693093 (-0.620) [0.5443]	-0.000496784 (-0.324) [0.7505]	-0.000303309 (-0.163) [0.8732]	-0.000572989 (-0.298) [0.7711]	-0.00116197 (-0.466) [0.6501]
$C^{2.33*4M^{-0.25}}$	-0.000105434 (-0.119) [0.9065]	-0.000319445 (-0.224) [0.8261]	-0.000362007 (-0.242) [0.8124]	-0.000480919 (-0.315) [0.7582]	8.197391E-6 (0.004) [0.9968]
$4M^{-0.25}$		14.6847 (0.195) [0.8482]	27.5718 (0.272) [0.7902]	84.3523 (0.664) [0.5194]	95.3184 (0.708) [0.4938]
$14M^{0.31}$			8.92931 (0.198) [0.8457]	74.3074 (0.767) [0.4578]	138.195 (0.726) [0.4829]
516M				-2.12742 (-0.766) [0.4587]	-7.80175 (-0.533) [0.6047]
$38M^2$					0.0373281 (0.395) [0.7002]
Df	15	14	13	12	11
N	20	20	20	20	20
r^2	0.39742	0.399051	0.400867	0.428768	0.436769
$\hat{\sigma}$	28.1177	29.0652	30.1168	30.6079	31.7443
r^2_{adj}	0.237	0.184	0.124	0.096	0.027
L2 $Y = \alpha + C^{2.33*}(\beta_1*38M^2 + \beta_2*516M + \beta_3*14M^{0.31} + \beta_4*4M^{-0.25})$					
L2A $Y = \alpha + C^{2.33*}(\beta_1*38M^2 + \beta_2*516M + \beta_3*14M^{0.31} + \beta_4*4M^{-0.25}) + \beta_5*4M^{-0.25}$					
L2B $Y = \alpha + C^{2.33*}(\beta_1*38M^2 + \beta_2*516M + \beta_3*14M^{0.31} + \beta_4*4M^{-0.25}) + \beta_5*4M^{-0.25} + \beta_6*14M^{0.31}$					
L2C $Y = \alpha + C^{2.33*}(\beta_1*38M^2 + \beta_2*516M + \beta_3*14M^{0.31} + \beta_4*4M^{-0.25}) + \beta_5*4M^{-0.25} + \beta_6*14M^{0.31} + \beta_7*516M$					
L2D $Y = \alpha + C^{2.33*}(\beta_1*38M^2 + \beta_2*516M + \beta_3*14M^{0.31} + \beta_4*4M^{-0.25}) + \beta_5*4M^{-0.25} + \beta_6*14M^{0.31} + \beta_7*516M + \beta_8*38M^2$					

of models presented in table E.4, the model L1 exhibited the largest adjusted R^2 value of 0.205 and was selected for further evaluation. Similarly, model L2 was selected from the set of models presented in table E.5 because it exhibited the largest adjusted R^2 value (0.237). Figure E.7 presents 2-dimensional plots of the actual versus predicted responses for models L1 and L2.

These models were further reduced (based on t-values) to eliminate explanatory variables that have no significant effect on the predicted response. This procedure involves removing predictors until no t-value satisfies $-t_{out} < t\text{-value} < t_{out}$. It is customary to use a t_{out} value of 2, since many t-critical values for a two-tailed test with a level of significance of 0.05 are close to this value (11). Tables E.6 and E.7 summarize the information concerning these reduced submodels for percent dilation per 100 cycles of freezing and thawing and durability factor, respectively.

From the models presented in tables E.6 and E.7, models L1b and L2a had the largest adjusted R^2 values of 0.256 and 0.284, respectively. Figure E.8 presents the actual versus predicted rapid freezing and thawing test results for these two models.

Figure E.7. Actual versus predicted rapid freezing and thawing test results for models L1 and L2 (percentage of mass passing, 4.75 to 12.5 mm [#4 to 0.5 in]).

Table E.6. Reduced multiple linear regression models for response variable “percent dilation per 100 cycles” (percentage of mass passing, 4.75 to 12.5 mm [#4 to 0.5 in]).

Variable	Estimates (t-value) [p-value]		
	Model Number		
	L1	L1a	L1b
Constant	0.00341740 (0.221) [0.8281]	0.00463338 (0.305) [0.7646]	0.00154258 (0.112) [0.9123]
$C^{2.33} * 38M^2$	-1.346140E-9 (-1.622) [0.1256]	-7.762051E-10 (-1.894) [0.0765]	-6.044320E-10 (-2.385) [0.0290]
$C^{2.33} * 516M$	9.199502E-8 (0.793) [0.4402]		
$C^{2.33} * 14M^{0.31}$	1.084382E-6 (0.811) [0.4303]	1.823883E-6 (1.924) [0.0723]	1.390784E-6 (2.807) [0.0121]
$C^{2.33} * 4M^{-0.25}$	9.663262E-8 (0.091) [0.9284]	-4.359265E-7 (-0.540) [0.5963]	
Df	15	16	17
N	20	20	20
r^2	0.372418	0.346116	0.334179
$\hat{\sigma}$	0.0336723	0.0332792	0.032579
r^2_{adj}	0.205	0.224	0.256
L1 $Y = \alpha + C^{2.33} * (\beta_1 * 38M^2 + \beta_2 * 516M + \beta_3 * 14M^{0.31} + \beta_4 * 4M^{-0.25})$			
L1a $Y = \alpha + C^{2.33} * (\beta_1 * 38M^2 + \beta_2 * 14M^{0.31} + \beta_3 * 4M^{-0.25})$			
L1b $Y = \alpha + C^{2.33} * (\beta_1 * 38M^2 + \beta_2 * 14M^{0.31})$			

Table E.7. Reduced multiple linear regression models for response variable “durability factor” (percentage of mass passing, 4.75 to 12.5 mm [#4 to 0.5 in]).

Variable	Estimates (t-value) [p-value]			
	Model Number			
	L2	L2a	L2b	L2c
Constant	93.5617 (7.245) [0.0000]	93.0188 (7.943) [0.0000]	95.9138 (8.067) [0.0000]	90.1184 (7.351) [0.0000]
$C^{2.33} * 38M^2$	1.312434E-6 (1.894) [0.0777]	1.291634E-6 (1.988) [0.0642]	4.097814E-7 (1.877) [0.0779]	
$C^{2.33} * 516M$	-0.000111392 (-1.150) [0.2683]	-0.000104036 (-1.436) [0.1704]		
$C^{2.33} * 14M^{0.31}$	-0.000693093 (-0.620) [0.5443]	-0.000814665 (-1.826) [0.0866]	-0.00105260 (-2.465) [0.0247]	-0.000295691 (-1.975) [0.0638]
$C^{2.33} * 4M^{-0.25}$	-0.000105434 (-0.119) [0.9065]			
Df	15	16	17	18
N	20	20	20	20
r^2	0.39742	0.396847	0.319153	0.178119
$\hat{\sigma}$	28.1177	27.2378	28.0749	29.9769
r_{adj}^2	0.237	0.284	0.239	0.132
L2 $Y = \alpha + C^{2.33} * (\beta_1 * 38M^2 + \beta_2 * 516M + \beta_3 * 14M^{0.31} + \beta_4 * 4M^{-0.25})$				
L2a $Y = \alpha + C^{2.33} * (\beta_1 * 38M^2 + \beta_2 * 516M + \beta_3 * 14M^{0.31})$				
L2b $Y = \alpha + C^{2.33} * (\beta_1 * 38M^2 + \beta_2 * 14M^{0.31})$				
L2c $Y = \alpha + C^{2.33} * (\beta_1 * 14M^{0.31})$

Figure E.8. Actual versus predicted rapid freezing and thawing test results for models L1b and L2a (percentage of mass passing, 4.75 to 12.5 mm [#4 to 0.5 in]).

E.2.2 Model Selection

At this point in the analysis, the best models would be further evaluated by checking the residual and model checking plots (as discussed in the preceding section 4.5.2.1) to ensure model adequacy. However, as illustrated in figures E.5 through E.8, there is a poor correlation between the hydraulic fracture test results for this size fraction (i.e., 4.75 to 12.5 mm [#4 to 0.5 in]) and rapid freezing and thawing test results (dilation and durability factor), so none of the models identified for this size fraction were evaluated further. The general lack of correlation also suggests that this particle size range has little, if any, effect on concrete freeze-thaw durability, as previously suggested by Schwartz (4) and others.

E.3 Initial Size Fraction: 12.5 to 19.0 mm (0.5 to 0.75 in)

Hydraulic fracture testing was performed on the initial size fraction 12.5 to 19.0 mm [0.5 to 0.75 in] using the procedures outlined in appendix A. The POMR and POPR on specified sieves were calculated for each replicate sample, along with the APOMR and APOPR for each source, using the equations presented in section 3.5.3. Tables D.3 and D.4 (see appendix D) present the mass and particle counts retained, respectively, on the specified sieves at 0 and 50 cycles for the

replicate samples for each source. The normalized mass and particle count retained data (i.e., POMR, APOMR, POPR and APOPR) are presented in tables D.5 and D.6 (see appendix D), respectively.

E.3.1 Mass Retained Data

E.3.1.1 Explanatory Variables

As stated previously, models were developed to predict percent dilation per 100 cycles of rapid freezing and thawing (dil) and durability factor (DF) as a function of the following explanatory variables:

58M:	Percentage of mass passing the 16.0-mm (0.625-in) screen.
12M:	Percentage of mass passing the 12.50-mm (0.5-in) screen.
38M:	Percentage of mass passing the 9.50-mm (0.375-in) screen.
516M:	Percentage of mass passing the 8.00-mm (0.3125-in) screen.
14M:	Percentage of mass passing the 6.35-mm (0.25-in) screen.
4M:	Percentage of mass passing the 4.75-mm (#4) screen.
C:	Percentage of carbonates present in source.

The percentage of mass passing each specified screen was calculated using the APOMR data presented in table D.5 and as defined below:

□ Total Percentage of Original Mass Retained [TPOMR] – *see equation E.1*

□ Percentage of mass passing the 16.0-mm (0.625-in) screen [58M]:

$$58M = TPOMR - APOMR_{58} \quad (\text{Eqn. E.15})$$

where: TPOMR = Total percentage of original mass retained and

APOMR₅₈ = average percentage of original mass retained on the 16.0-mm (0.625-in) screen.

□ Percentage of mass passing the 12.5-mm (0.5-in) screen [12M]:

$$12M = 58M - APOMR_{12} \quad (\text{Eqn. E.16})$$

where: 58M = Percentage of mass passing the 16.0-mm (0.625-in) screen and

APOMR₁₂ = average percentage of original mass retained on the 12.5-mm (0.5-in) screen.

- Percentage of mass passing the 9.50-mm (0.375-in) screen [38M]:

$$38M = 12M - \text{APOMR}_{38} \quad (\text{Eqn. E.17})$$

where: 12M = Percentage of mass passing the 12.5-mm (0.5-in) screen and

APOMR₃₈ = average percentage of original mass retained on the 9.50-mm (0.375-in) screen.

- Percentage of mass passing the 8.00-mm (0.3125-in) screen [516M] – *see equation E.3*

- Percentage of mass passing the 6.35-mm (0.25-in) screen [14M] – *see equation E.4*

- Percentage of mass passing the 4.75-mm (#4) screen [4_{actual}] – *see equation E.5*

- Percentage of mass lost due to testing [M_{loss}] – *see equation E.6*

- Percentage of mass passing the 4.75-mm (#4) screen (adjusted for mass loss during testing) [4M] – *see equation E.7*

- Percentage of mass passing the pan [pan] – *see equation E.8*

The predictors defined by equations E.3 to E.4, E.7 and E.15 to E.17 were calculated for each of 20 sources and then transferred as an *lsp* file into *ARC*. Equation E.8 was used as a check to make sure that there were no computational errors.

It should be noted that as much as one percent of the mass of a given test sample was sometimes lost during testing. As a result, the total percentage of original material mass retained during the final sieve analyses was sometimes reduced to 99 percent or more. Because of the great care taken during testing, it was assumed that the material lost during testing was probably very fine

and would have passed the 4.75-mm (#4 sieve). Equations E.5 to E.7 were developed to account for this mass loss and attribute it to the proper particle size in the regression analysis.

E.3.1.2 Transformations to Normality

Two-dimensional scatter plots were developed to show the conditional distribution of the response variables (dilation/100 cycles and durability factor) given changes in each explanatory variable. Normality is achieved when the mean functions are linear and the variance functions are constant (9). The scatter plot matrix for the previously defined explanatory and response variables is presented in figure E.9, which shows that there is little normality between the response and explanatory variables in the inverse fitted value plots (marginal distribution plots).

Figure E.9. Scatter plot matrix for responses and explanatory variables (percentage of mass passing, 12.5 to 19.0 mm [0.5 to 0.75 in]).

Normality can sometimes be achieved or improved through transformations of the explanatory variables. In this study, explanatory variable transformations were performed using the Box-Cox method (a numerical procedure) in an attempt to improve the linearity of the relationships.

Figure E.10 presents the scatter plot matrix for the transformed explanatory variables and shows that the Box-Cox transformations were not effective in producing linear relationships between the percentage of mass passing the designated screens and either percent dilation or the durability factor.

Figure E.10. Scatter plot matrix for responses and transformed explanatory variables (percentage of mass passing, 12.5 to 19.0 mm [0.5 to 0.75 in]).

Even though normality was apparently not achieved, nonlinear and multiple linear regression analyses were performed on this data set, as described below in subsection F3.1.3.

E.3.1.3 Nonlinear and Multiple Linear Regression

As stated previously, past studies have shown that concrete freeze-thaw durability is often a function of carbonate content. Therefore, the following general nonlinear model form was adopted:

$$E(y|x) = C*(\text{linear combination of } 58M, 12M, 38M, 516M, 14M \text{ and } 4M)$$

therefore,

$$E(y|x) = C*(\alpha + \beta_1*58M + \beta_2*12M + \beta_3*38M + \beta_4*516M + \beta_5*14M + \beta_6*4M) \quad (\text{Eqn. E.18})$$

Equation E.18 was modified slightly for multiple linear regression to produce basic forms for modeling dilation and durability factor as a function of percentages of mass passing the specified sieves either with or without an interaction term for carbonate content:

$$E(y|x) = \alpha + \beta_1*C*38M + \beta_2*C*516M + \beta_3*C*14M + \beta_4*C*4M \quad (\text{Eqn. E.19})$$

$$E(y|x) = \alpha + \beta_1*38M + \beta_2*516M + \beta_3*14M + \beta_4*4M \quad (\text{Eqn. E.20})$$

Regression analyses were performed using the model forms presented in equations E.18 through E.20 with both the transformed and untransformed (identity) explanatory variables. Numerous nonlinear and multiple linear regression models were formulated in the manner described previously in section E.2.1.3; however, only the models with the best adjusted R^2 for the response variables percentage of dilation per 100 cycles (model N1) and durability factor (model L2) were recorded in tables E.8 and E.9, respectively. As described previously, these models were reduced to eliminate predictors that have no significant effect on the mean function. The reduced models are designated with lowercase letters behind the model number (e.g., N1a, N1b, etc.).

E.3.1.4 Model Selection

The F-statistic was used to determine the most compact model that adequately represents the data. The F-statistic is expressed as follows (9):

Table E.8. Nonlinear regression models for response variable “percent dilation per 100 cycles” (percentage of mass passing, 12.5 to 19.0 mm [0.5 to 0.75 in]).

Variable	Estimates (Wald Test)				
	Model Number				
	N1	N1a	N1b	N1c	N1d
α	-0.0000106798 (-1.209)	-0.0000101023 (-1.318)	-4.883484E-6 (-0.672)	-5.680484E-6 (-0.811)	-4.421358E-6 (-0.695)
58M	5.610871E-7 (2.597)	5.421653E-7 (3.206)	4.369152E-7 (2.678)	4.397408E-7 (2.752)	4.242641E-7 (2.771)
12M	-1.390522E-6 (-3.297)	-1.361274E-6 (-3.776)	-1.300747E-6 (-3.458)	-1.277577E-6 (-3.484)	-1.237859E-6 (-3.543)
38M	-0.0000381508 (-1.506)	-0.0000386800 (-1.598)	-0.0000103731 (-0.606)		
516M	0.0000988808 (1.528)	0.000101786 (1.709)	0.0000114510 (0.636)	5.626926E-7 (0.488)	
14M	-0.0000617554 (-1.438)	-0.0000634044 (-1.584)			
4M	1.326474E-6 (0.150)				
Df	13	14	15	16	17
N	20	20	20	20	20
r^2	0.7682	0.7678	0.7262	0.7195	0.7154
$\hat{\sigma}$	0.0279457	0.0269524	0.0282751	0.0277104	0.0270823
r^2_{adj}	0.633	0.661	0.628	0.645	0.662
Models Compared		(N1) – (N1a)	(N1b) – (N1a)	(N1c) – (N1b)	(N1d) – (N1c)
P-value		0.883	0.136	0.554	0.632
^{N1} $Y = C^2 * (\alpha + \beta_1 * 58M + \beta_2 * 12M + \beta_3 * 38M + \beta_4 * 516M + \beta_5 * 14M + \beta_6 * 4M)$					
^{N1a} $Y = C^2 * (\alpha + \beta_1 * 58M + \beta_2 * 12M + \beta_3 * 38M + \beta_4 * 516M + \beta_5 * 14M)$					
^{N1b} $Y = C^2 * (\alpha + \beta_1 * 58M + \beta_2 * 12M + \beta_3 * 38M + \beta_4 * 516M)$					
^{N1c} $Y = C^2 * (\alpha + \beta_1 * 58M + \beta_2 * 12M + \beta_4 * 516M)$					
^{N1d} $Y = C^2 * (\alpha + \beta_1 * 58M + \beta_2 * 12M)$					

Table E.9. Multiple linear regression models for response variable “durability factor” (percentage of mass passing, 12.5 to 19.0 mm [0.5 to 0.75 in]).

Variable	Estimates (t-value)				
	Model Number				
	L2	L2a	L2b	L2c	L2d
α	131.213 (8.780)	132.440 (9.218)	133.817 (9.029)	131.110 (8.728)	131.136 (8.995)
58M*C	-0.0351875 (-3.746)	-0.0375415 (-4.684)	-0.0357316 (-4.367)	-0.0360867 (-4.312)	-0.0362704 (-4.543)
12M*C	0.100410 (3.403)	0.105734 (3.924)	0.101912 (3.676)	0.106834 (3.800)	0.106529 (3.921)
38M*C	2.60891 (1.461)	2.43465 (1.426)			
516M*C	-8.62253 (-1.896)	-7.61122 (-1.901)	-2.55638 (-1.328)	-0.0105120 (-0.119)	
14M*C	5.96333 (1.964)	5.30450 (1.974)	2.68182 (1.324)		
4M*C	0.328906 (0.520)				
Df	13	14	15	16	17
N	20	20	20	20	20
R^2	0.672914	0.6661	0.617604	0.572896	0.572515
$\hat{\sigma}$	22.2524	21.6652	22.399	22.9206	22.2461
R^2_{adj}	0.522	0.547	0.516	0.493	0.522
Models Compared		(N1) – (N1a)	(N1b) – (N1a)	(N1c) – (N1b)	(N1d) – (N1c)
P-value		0.6115	0.1758	0.2052	0.9064
$L2 \ Y = \alpha + C*(\beta_1*58M + \beta_2*12M + \beta_3*38M + \beta_4*516M + \beta_5*14M + \beta_6*4M)$ $L2a \ Y = \alpha + C*(\beta_1*58M + \beta_2*12M + \beta_3*38M + \beta_4*516M + \beta_5*14M)$ $L2b \ Y = \alpha + C*(\beta_1*58M + \beta_2*12M + \beta_3*516M + \beta_4*14M)$ $L2c \ Y = \alpha + C*(\beta_1*58M + \beta_2*12M + \beta_3*516M)$ $L2d \ Y = \alpha + C*(\beta_1*58M + \beta_2*12M)$					

Null Hypothesis (NH): data is adequately represented by nested (smaller) model

Alternative Hypothesis (AH): data is adequately represented by larger model

$$F = \frac{(RSS_{NH} - RSS_{AH}) / (df_{NH} - df_{AH})}{\hat{\sigma}_{AH}^2} \quad (\text{Eqn. E.21})$$

where: RSS_{AH} = residual sum of squares for AH model, with df_{AH} degrees of freedom;
 RSS_{NH} = residual sum of squares for NH model, with df_{NH} degrees of freedom; and
 $\hat{\sigma}_{AH}^2 = RSS_{AH} / df_{AH}$ = residual mean square for AH model.

The p-value to determine whether to reject or accept the NH is obtained by comparing F to the F distribution with $(df_{NH} - df_{AH}, df_{AH})$ degrees of freedom.

The F-statistic was calculated for each comparison (e.g., NH: N1a versus AH: N1, etc.) to identify the most compact model that adequately captures the data. As illustrated in tables E.8 and E.9, where all p-values are greater than 0.05, each nested model will adequately represent the data. Therefore, graphs of actual versus predicted rapid freezing and thawing test results (summary plot) and model checking plots were produced to determine the model that most adequately represents the data. The following model checking plots were constructed to check the mean function (9):

- Marginal Plots: Marginal plots are multipanel plots of the response variable versus the fitted values ($\eta'u$) and versus selected predictors (e.g., 58M, 12M, etc.).
- GREG (Graphical Regression) Plots: The first GREG plot selects a linear combination of the selected terms that is most likely to show curvature in the plot of residuals versus that linear combination (i.e., the first GREG plot is an approximation of the worst case). The remaining GREG linear combinations are uncorrelated with the first GREG linear combination, and each is less likely than the one before to show curvature. These plots are multi-panel plots of the response variable versus GREG linear combinations.

- Random Plots: Random plots are multi-panel plots of the response variable versus a random linear combination of the selection.

A visual assessment of a model's capability of reproducing the information provided by the available data is performed by comparing the smooths (i.e., the response versus fitted values [mean function]). The model has the correct mean function if and only if the model checking plots agree (i.e., the two smooths are equal) for all of the model checking plots (9). In addition to the above plots, a nonconstant variance plot and residual plots (residuals versus predictors and versus fitted values) were constructed to determine the adequacy of the models.

The models shaded in gray in tables E.8 and E.9 (i.e., N1a and L2a) are the final models chosen based on the model checking plots. Figure E.11 presents the summary plots for models N1a and L2a.

Figure E.11. Actual versus predicted rapid freezing and thawing test results for models N1a and L2a (percentage of mass passing, 12.5 to 19.0 mm [0.5 to 0.75 in]).

As illustrated in these plots, the correlation between the hydraulic fracture and freezing and thawing data is increased over that obtained for the 4.75-to 12.5-mm (#4 to 0.5 in) initial size

fraction. However, the correlation achieved by these mean functions is still not sufficiently strong.

E.3.2 Particle Count Data

E.3.2.1 Explanatory Variables

As stated previously, models were developed to predict percent dilation per 100 cycles of rapid freezing and thawing (dil) and durability factor (DF) as a function of the following explanatory variables:

58P:	Percentage of particles passing the 16.0-mm (0.625-in) screen.
12P:	Percentage of particles passing the 12.50-mm (0.5-in) screen.
38P:	Percentage of particles passing the 9.50-mm (0.375-in) screen.
516P:	Percentage of particles passing the 8.00-mm (0.3125-in) screen.
14P:	Percentage of particles passing the 6.35-mm (0.25-in) screen.
4P:	Percentage of particles passing the 4.75-mm (#4) screen.
C:	Percentage of carbonates present in source.

The percentage of particles passing each specified screen was calculated using the AOPR data presented in table D.6 and defined below:

□ Total Percentage of Original Particles Retained [TPOPR]:

$$\text{TPOPR} = \sum_{i=1}^n \text{AOPR}_i \quad (\text{Eqn. E.22})$$

where: AOPR_i = average percentage of original particles retained on screen i and
 n = total number of screens.

□ Percentage of particles passing the 16.0-mm (0.625-in) screen [58P]:

$$58\text{P} = \text{TPOPR} - \text{AOPR}_{58} \quad (\text{Eqn. E.23})$$

where: TPOPR = Total percentage of original particles retained and
 AOPR_{58} = average percentage of original particles retained on the 16.0-mm (0.625-in) screen.

- Percentage of particles passing the 12.5-mm (0.5-in) screen [12P]:

$$12P = 58P - APOPR_{12} \quad (\text{Eqn. E.24})$$

where: 58P = Percentage of particles passing the 16.0-mm (0.625-in) screen and

APOPR₁₂ = average percentage of original particles retained on the 12.5-mm (0.5-in) screen.

- Percentage of particles passing the 9.50-mm (0.375-in) screen [38P]:

$$38P = 12P - APOPR_{38} \quad (\text{Eqn. E.25})$$

where: 12P = Percentage of particles passing the 12.5-mm (0.5-in) screen and

APOPR₃₈ = average percentage of original particles retained on the 9.50-mm (0.375-in) screen.

- Percentage of particles passing the 8.00-mm (0.3125-in) screen [516P]:

$$516P = 38P - APOPR_{516} \quad (\text{Eqn. E.26})$$

where: 38P = Percentage of particles passing the 9.50-mm (0.375-in) screen and

APOPR₅₁₆ = average percentage of original particles retained on the 8.00-mm (0.3125-in) screen.

- Percentage of particles passing the 6.35-mm (0.25-in) screen [14P]:

$$14P = 516P - APOPR_{14} \quad (\text{Eqn. E.27})$$

where: 516P = Percentage of particles passing the 8.00-mm (0.3125-in) screen and

APOPR₁₄ = average percentage of original particles retained on the 6.35-mm (0.25-in) screen.

- Percentage of particles passing the 4.75-mm (#4) screen [4P]:

$$4P = 14P - APOPR_4 \quad (\text{Eqn. E.28})$$

where: 14P = Percentage of particles passing the 6.35-mm (0.25-in) screen and

APOPR₄ = average percentage of original particles retained on the 4.75-mm (#4) screen.

□ Percentage of particles passing the pan [pan]:

$$\text{Pan} = 4P - \text{AOPR}_{\text{pan}} = 0 \quad (\text{Eqn. E.29})$$

where: $4P$ = Cumulative percentage of particles passing the 4.75-mm (#4) screen and

AOPR_{pan} = average percentage of original particles retained on the pan.

The predictors defined by equations E.23 to E.28 were calculated for each of 20 sources and then transferred as an *lsp* file into *ARC*. Equation E.29 was used as a check to make sure that there were no computational errors.

It should be noted, the TPOPR may be greater than 100 percent due to the fracturing of particles during testing, which may increase the number of particles retained to a number greater than the original number of particles.

E.3.2.2 Transformations to Normality

Two-dimensional scatter plots were developed to show the conditional distributions of the response variables (dilation/100 cycles and durability factor) given changes in each explanatory variable. The scatter plot matrix for the above explanatory and response variables is presented in figure E.12. Normality is achieved when the mean functions are linear and the variance functions are constant (9). As illustrated in figure E.12, there is a lack of normality between the response and explanatory variables in the inverse fitted value plots (marginal distribution plots).

Normality can sometimes be achieved or improved through transformations of the explanatory variables. In this study, explanatory variable transformations were performed using the Box-Cox method (a numerical procedure) in an attempt to improve the linearity of the relationships. Figure E.13 presents the scatter plot matrix for the transformed explanatory variables.

E.3.2.3 Nonlinear and Multiple Linear Regression

As stated previously, past studies have shown that concrete freeze-thaw durability is often a function of carbonate content. Therefore, the following general nonlinear model form was adopted:

$$E(y|x) = C * (\text{linear combination of } 58P, 12P, 38P, 516P, 14P \text{ and } 4P)$$

therefore,

$$E(y|x) = C * (\alpha + \beta_1 * 58P + \beta_2 * 12P + \beta_3 * 38P + \beta_4 * 516P + \beta_5 * 14P + \beta_6 * 4P) \quad (\text{Eqn. E.30})$$

Figure E.12. Scatter plot matrix for responses and explanatory variables (percentage of particles passing, 12.5 to 19.0 mm [0.5 to 0.75 in]).

Figure E.13. Scatter plot matrix for responses and transformed explanatory variables (percentage of particles passing, 12.5 to 19.0 mm [0.5 to 0.75 in]).

Equation E.30 was modified slightly for multiple linear regression to produce basic forms for modeling dilation and durability factor as a function of percentages of particle counts passing the specified sieves either with or without an interaction term for carbonate content:

$$E(y|x) = \alpha + \beta_1 * C * 38P + \beta_2 * C * 516P + \beta_3 * C * 14P + \beta_4 * C * 4P \quad (\text{Eqn. E.31})$$

$$E(y|x) = \alpha + \beta_1 * 38P + \beta_2 * 516P + \beta_3 * 14P + \beta_4 * 4P \quad (\text{Eqn. E.32})$$

Regression analyses were performed using the model forms presented in equations E.30 through E.32 with both the transformed and untransformed (identity) explanatory variables. Numerous nonlinear and multiple linear regression models were formulated (as discussed previously in section E.2.1.3); however, only the models with the best adjusted R^2 for the response variables, percentage of dilation per 100 cycles (model N1) and durability factor (model N2), were recorded in tables E.10 and E.11, respectively. As described previously, these models were reduced to eliminate predictors that have no significant effect on the mean function. The reduced models are designated with lowercase letters behind the model number (e.g., N1a, N1b, etc.).

Table E.10. Nonlinear regression models for response variable “percent dilation per 100 cycles” (percentage of particles passing, 12.5 to 19.0 mm [0.5 to 0.75 in]).

Parameter	Estimate (Wald Test)	
	Model Number	
	N1	N1a
α	-0.000341181 (-2.650)	-0.000354118 (-2.867)
$58P^{0.2}$	0.000174131 (3.163)	0.000177586 (3.329)
$12P^{0.67}$	-5.871615E-6 (-4.000)	-5.712814E-6 (-4.067)
$38P^{0.61}$	-0.0000550154 (-2.068)	-0.0000565347 (-2.190)
$516P^{0.58}$	0.000123224 (2.656)	0.000118035 (2.663)
$14P^{0.5}$	-0.0000958431 (-1.814)	-0.0000739097 (-2.140)
$4P^{0.5}$	0.0000129321 (0.560)	
Df	13	14
N	20	20
r^2	0.8107	0.8061
$\hat{\sigma}^2$	0.025257	0.0246296
r^2_{adj}	0.700	0.717
Models Compared		(N1) – (N1a)
P-value		0.5853
$N1 \ Y = C^{1.9} * (\alpha + \beta_1 * 58P^{0.2} + \beta_2 * 12P^{0.67} + \beta_3 * 38P^{0.61} + \beta_4 * 516P^{0.58} + \beta_5 * 14P^{0.5} + \beta_6 * 4P^{0.5})$		
$N1a \ Y = C^{1.9} * (\alpha + \beta_1 * 58P^{0.2} + \beta_2 * 12P^{0.67} + \beta_3 * 38P^{0.61} + \beta_4 * 516P^{0.58} + \beta_5 * 14P^{0.5})$		

Table E.11. Multiple linear regression models for “durability factor”
(percentage of particles passing, 12.5 to 19.0 mm [0.5 to 0.75 in]).

Variable	Estimates (t-value)								
	Model Number								
	L2	L2a	L2b	L2c	L2d	L2e	L2f	L2g	L2h
α	2165.66 (2.733)	2194.42 (3.310)	2178.82 (3.493)	2156.42 (3.637)	2216.63 (3.751)	2247.27 (3.943)	2264.92 (4.118)	2345.11 (4.095)	2217.49 (3.782)
$58P^{0.2}*C$	-0.453014 (-0.194)	-0.302439 (-0.229)							
$12P^{0.67}*C$	0.0213513 (0.081)								
$38P^{0.61}*C$	6.84710 (1.059)	6.92971 (1.160)	6.77741 (1.207)	4.90117 (2.734)	4.73988 (2.649)	4.63603 (2.690)	4.52632 (2.748)	2.52554 (2.427)	3.01206 (2.951)
$516P^{0.58}*C$	-9.78372 (-0.947)	-9.52611 (-1.036)	-8.22333 (-1.203)	-5.96756 (-2.503)	6.10594 (-2.561)	-5.40820 (-2.826)	-5.28112 (-2.889)	-3.08762 (-2.621)	-3.61041 (-3.106)
$14P^{0.5}*C$	-2.42177 (-0.141)	-3.22717 (-0.247)	-5.77964 (-0.898)	-4.03206 (-1.021)					
$4P^{0.5}*C$	5.31704 (0.533)	5.64498 (0.661)	6.57690 (0.927)	4.53999 (1.142)	0.770985 (0.522)				
$4P^{0.5}$	-567.483 (-0.578)	-597.903 (-0.704)	-690.919 (-0.980)	-490.973 (-1.213)	-134.711 (-0.657)	-46.8428 (-0.413)			
$14P^{0.5}$	628.056 (0.384)	702.054 (0.552)	939.617 (1.354)	772.495 (1.589)	356.153 (1.343)	291.795 (1.282)	218.344 (1.590)	9.26094 (1.451)	
$516P^{0.58}$	354.196 (0.383)	327.660 (0.405)	215.650 (0.355)						
$38P^{0.61}$	-365.277 (-0.625)	-370.033 (-0.681)	-360.626 (-0.703)	-184.238 (-1.544)	-136.145 (-1.240)	-153.261 (-1.509)	-135.301 (-1.524)		
$12P^{0.67}$	31.9455 (1.212)	33.9394 (3.875)	34.3164 (4.217)	34.4101 (4.429)	33.2394 (4.318)	33.1330 (4.442)	32.5069 (4.600)	31.3148 (4.262)	31.5134 (4.140)
$58P^{0.2}$	-980.100 (-2.144)	-1005.89 (-3.278)	-1028.20 (-3.736)	-1020.47 (-3.894)	-1033.27 (-3.940)	-1039.64 (-4.094)	-1040.46 (-4.235)	-1040.08 (-4.047)	-979.265 (-3.727)
Df	7	8	9	10	11	12	13	14	15
N	20	20	20	20	20	20	20	20	
r^2	0.773148	0.772935	0.77145	0.768256	0.744111	0.73777	0.734047	0.686552	0.639432
$\hat{\sigma}$	25.2546	23.6346	22.3557	21.3561	21.3967	20.7381	20.0654	20.9912	21.7504
r^2_{adj}	0.384	0.461	0.518	0.560	0.558	0.585	0.611	0.575	0.543
Models Compared		(N1) – (N1a)	(N1b) – (N1a)	(N1c) – (N1b)	(N1d) – (N1c)	(N1e) – (N1d)	(N1f) – (N1e)	(N1g) – (N1f)	(N1h) – (N1g)

Table E.11. Multiple linear regression models for “durability factor”
(percentage of particles passing, 12.5 to 19.0 mm [0.5 to 0.75 in]) (continued).

Variable	Estimates (t-value)								
	Model Number								
	L2	L2a	L2b	L2c	L2d	L2e	L2f	L2g	L2h
P-value		0.9377	0.8248	0.7311	0.3314	0.612	0.6871	0.1515	0.1689
L2	$Y = \alpha + C*(\beta_1*58P^{0.2} + \beta_2*12P^{0.67} + \beta_3*38P^{0.61} + \beta_4*516P^{0.58} + \beta_5*14P^{0.5} + \beta_6*4P^{0.5})$ $+ \beta_7*4P^{0.5} + \beta_8*14P^{0.5} + \beta_9*516P^{0.58} + \beta_{10}*38P^{0.61} + \beta_{11}*12P^{0.67} + \beta_{12}*58P^{0.2}$								
L2a	$Y = \alpha + C*(\beta_1*58P^{0.2} + \beta_2*38P^{0.61} + \beta_3*516P^{0.58} + \beta_4*14P^{0.5} + \beta_5*4P^{0.5})$ $+ \beta_6*4P^{0.5} + \beta_7*14P^{0.5} + \beta_8*516P^{0.58} + \beta_9*38P^{0.61} + \beta_{10}*12P^{0.67} + \beta_{11}*58P^{0.2}$								
L2b	$Y = \alpha + C*(\beta_1*38P^{0.61} + \beta_2*516P^{0.58} + \beta_3*14P^{0.5} + \beta_4*4P^{0.5}) + \beta_5*4P^{0.5} + \beta_6*14P^{0.5} + \beta_7*516P^{0.58} + \beta_8*38P^{0.61} + \beta_9*12P^{0.67} + \beta_{10}*58P^{0.2}$								
L2c	$Y = \alpha + C*(\beta_1*38P^{0.61} + \beta_2*516P^{0.58} + \beta_3*14P^{0.5} + \beta_4*4P^{0.5}) + \beta_5*4P^{0.5} + \beta_6*14P^{0.5} + \beta_7*38P^{0.61} + \beta_8*12P^{0.67} + \beta_9*58P^{0.2}$								
L2d	$Y = \alpha + C*(\beta_1*38P^{0.61} + \beta_2*516P^{0.58} + \beta_3*4P^{0.5}) + \beta_4*4P^{0.5} + \beta_5*14P^{0.5} + \beta_6*38P^{0.61} + \beta_7*12P^{0.67} + \beta_8*58P^{0.2}$								
L2e	$Y = \alpha + C*(\beta_1*38P^{0.61} + \beta_2*516P^{0.58}) + \beta_3*4P^{0.5} + \beta_4*14P^{0.5} + \beta_5*38P^{0.61} + \beta_6*12P^{0.67} + \beta_7*58P^{0.2}$								
L2f	$Y = \alpha + C*(\beta_1*38P^{0.61} + \beta_2*516P^{0.58}) + \beta_3*14P^{0.5} + \beta_4*38P^{0.61} + \beta_5*12P^{0.67} + \beta_6*58P^{0.2}$								
L2g	$Y = \alpha + C*(\beta_1*38P^{0.61} + \beta_2*516P^{0.58}) + \beta_3*14P^{0.5} + \beta_4*12P^{0.67} + \beta_5*58P^{0.2}$								
L2h	$Y = \alpha + C*(\beta_1*38P^{0.61} + \beta_2*516P^{0.58}) + \beta_3*12P^{0.67} + \beta_6*58P^{0.2}$								

E.3.2.4 Model Selection

As described previously, the F-statistic was calculated for each comparison to determine the smallest model that adequately describes the data. As illustrated in tables E.10 and E.11, where all p-values are greater than 0.05, each nested model adequately represents the data. Therefore, the summary, residual, nonconstant variance and model checking plots were produced to determine which model most adequately represents the data.

The models shaded in gray in tables E.10 and E.11 (N1 and L2f) were the final models chosen, based on the plots described above. Figure E.14 presents the summary plots for models N1a and L2f. As illustrated in these plots, the correlation between the hydraulic fracture test data and the freezing and thawing test data was stronger for the particle count data than for the mass data for this size fraction. The mean function for the models illustrated in figure E.14 appears to do a fair job of representing the data.

Figure E.14. Actual versus predicted rapid freezing and thawing test results for models N1a and L2f (percentage of particles passing, 12.5 to 19.0 mm [0.5 to 0.75 in]).

E.4 Initial Size Fraction: 19.0 to 37.5 mm (0.75 to 1.5 in)

Hydraulic fracture testing was performed on the initial size fraction 19.0 to 37.5 mm [0.75 to 1.5 in] using the procedures outlined in Appendix A. The POMR and POPR on specified sieves were calculated for each replicate sample, along with the APOMR and APOPR for each source, using the equations presented in section 3.5.3. Tables D.7 and D.8 (see appendix D) present the mass and particle counts retained, respectively, on the specified sieves at 0 and 50 cycles for the replicate samples for each source. The normalized mass and particle count retained data (i.e., POMR, APOMR, POPR and APOPR) are presented in tables D.9 and D.10 (see appendix D), respectively.

E.4.1 Mass Retained Data

E.4.1.1 Explanatory Variables

As stated previously, models were developed to predict percent dilation per 100 cycles of rapid freezing and thawing (dil) and durability factor (DF) as a function of the following explanatory variables:

1M:	Percentage of mass passing the 25.0-mm (1-in) screen.
34M:	Percentage of mass passing the 19.0-mm (0.75-in) screen.
58M:	Percentage of mass passing the 16.0-mm (0.625-in) screen.
12M:	Percentage of mass passing the 12.50-mm (0.5-in) screen.
38M:	Percentage of mass passing the 9.50-mm (0.375-in) screen.
516M:	Percentage of mass passing the 8.00-mm (0.3125-in) screen.
14M:	Percentage of mass passing the 6.35-mm (0.25-in) screen.
4M:	Percentage of mass passing the 4.75-mm (#4) screen.
C:	Percentage of carbonates present in source.

The percentage of mass passing each specified screen was calculated using the APOMR data presented in table D.9 as defined below:

- Total Percentage of Original Mass Retained [TPOMR] – *see equation E.1*
- Percentage of mass passing the 25.0-mm (1-in) screen [1M]:

$$1M = TPOMR - APOMR_1 \quad (\text{Eqn. E.33})$$

where: TPOMR = Total percentage of original mass retained and

APOMR₁ = average percentage of original mass retained on the 25.0-mm (1-in) screen.

- Percentage of mass passing the 19.0-mm (0.75-in) screen [34M]:

$$34M = 1M - APOMR_{34} \quad (\text{Eqn. E.34})$$

where: 1M = Percentage of mass passing the 25.0-mm (1-in) screen and

APOMR₃₄ = average percentage of original mass retained on the 19.0-mm (0.75-in) screen.

- Percentage of mass passing the 16.0-mm (0.625-in) screen [58M]:

$$58M = 34M - APOMR_{58} \quad (\text{Eqn. E.35})$$

where: 34M = Percentage of mass passing the 19.0-mm (0.75-in) screen and

APOMR₅₈ = average percentage of original mass retained on the 16.0-mm (0.625-in) screen.

- Percentage of mass passing the 12.5-mm (0.5-in) screen [12M] – *see equation E.16*

- Percentage of mass passing the 9.50-mm (0.375-in) screen [38M] – *see equation E.17*

- Percentage of mass passing the 8.00-mm (0.3125-in) screen [516M] – *see equation E.3*

- Percentage of mass passing the 6.35-mm (0.25-in) screen [14M] – *see equation E.4*

- Percentage of mass passing the 4.75-mm (#4) screen [4_{actual}] – *see equation E.5*

- Percentage of mass lost due to testing [M_{loss}] – *see equation E.6*

- Percentage of mass passing the 4.75-mm (#4) screen (adjusted for mass loss during testing) [4M] – *see equation E.7*

- Percentage of mass passing the pan [pan] – *see equation E.8*

The predictors defined by equations E.3 to E.5, E.7, E.16, E.17 and E.33 to E.35 were calculated for each of 19 sources and then transferred as an *lsp* file into *ARC*. Equation E.8 was used as a check to make sure that there were no computational errors.

It should be noted that as much as one percent of the mass of a given test sample was sometimes lost during testing. As a result, the total percentage of original material mass retained during the final sieve analyses was sometimes reduced to 99 percent or more. Because of the great care taken during testing, it was assumed that the material lost during testing was probably very fine and would have passed the 4.75-mm (#4 sieve). Equations E.5 to E.7 were developed to account for this mass loss and attribute it to the proper particle size in the regression analysis.

E.4.1.2 Transformations to Normality

Two-dimensional scatter plots were developed to show the conditional distribution of the response variables (dilation/100 cycles and durability factor) given changes in each explanatory variable. The scatter plot matrix for the previously described explanatory and response variables is presented in figure E.15.

Normality is achieved when the mean functions are linear and the variance functions are constant (9). As illustrated in figure E.15, there is a lack of normality between the response and explanatory variables in the inverse fitted value plots (marginal distribution plots).

Normality can sometimes be achieved or improved through transformations of the explanatory variables. In this study, explanatory variable transformations were performed using the Box-Cox method (a numerical procedure) in an attempt to improve the linearity of the relationships. Figure E.16 presents the scatter plot matrix for the transformed explanatory variables.

E.4.1.3 Nonlinear and Multiple Linear Regression

As stated previously, past studies have shown that concrete freeze-thaw durability is often a function of carbonate content. Therefore, the following general nonlinear model form was

Figure E.15. Scatter plot matrix for responses and explanatory variables (percentage of mass passing, 19.0 to 37.5 mm [0.75 to 1.5 in]).

Figure E.15. Scatter plot matrix for responses and explanatory variables (percentage of mass passing, 19.0 to 37.5 mm [0.75 to 1.5 in]) (continued).

Figure E.16. Scatter plot matrix for responses and transformed explanatory variables (percentage of mass passing, 19.0 to 37.5 mm [0.75 to 1.5 in]).

Figure E.16. Scatter plot matrix for responses and transformed explanatory variables (percentage of mass passing, 19.0 to 37.5 mm [0.75 to 1.5 in]) (continued).

adopted:

$$E(y|x) = C*(\text{linear combination of 1M, 34M, 58M, 12M, 38M, 516M, 14M and 4M})$$

therefore,

$$E(y|x) = C*(\alpha + \beta_1*1M + \beta_2*34M + \beta_3*58M + \beta_4*12M + \beta_5*38M + \beta_6*516M + \beta_7*14M + \beta_8*4M) \quad (\text{Eqn. E.36})$$

Equation E.36 was modified slightly for multiple linear regression to produce basic forms for modeling dilation and durability factor as a function of percentages of mass passing the specified sieves either with or without an interaction term for carbonate content:

$$E(y|x) = \alpha + \beta_1*C*1M + \beta_2*C*34M + \beta_3*C*58M + \beta_4*C*12M + \beta_5*C*38M + \beta_6*C*516M + \beta_7*C*14M + \beta_8*C*4M \quad (\text{Eqn. E.37})$$

$$E(y|x) = \alpha + \beta_1*1M + \beta_2*34M + \beta_3*58M + \beta_4*12M + \beta_5*38M + \beta_6*516M + \beta_7*14M + \beta_8*4M \quad (\text{Eqn. E.38})$$

Regression analyses were performed using the model forms presented in equations E.36 through E.38 with both the transformed and untransformed (identity) explanatory variables. Numerous nonlinear and multiple linear regression models were formulated in the manner described previously in section E.2.1.3; however, only the models with the best adjusted R^2 for the response variables (percentage of dilation per 100 cycles [model L1] and durability factor [model N2]), were recorded in tables E.12 and E.13, respectively.

As described previously, these models were reduced to eliminate predictors that have no significant effect on the mean function. The reduced models are designated with lowercase letters behind the model number (e.g., N1a, N1b, etc.).

E.4.1.4 Model Selection

The F-statistic was calculated for each comparison to identify the most compact model that adequately represents the data. As illustrated in tables E.12 and E.13, where all p-values are greater than 0.05, each nested model adequately represents the data. Therefore, as described in

previous subsections, the summary, residual, nonconstant variance and model checking plots were produced to identify the model that best represents the data.

Table E.12. Nonlinear regression models for response variable “percent dilation per 100 cycles” (percentage of mass passing, 19.0 to 37.5 mm [0.75 to 1.5 in]).

Variable	Estimates (Wald Statistic) [p-value]					
	Model Number					
	N1	N1a	N1b	N1c	N1a*	N1a**
α	-3.333247E-8 (-0.680) [0.4967]	-1.029989E-8 (-0.587) [0.5573]	-2.049791E-8 (-1.247) [0.2125]	-2.063279E-8 (-1.174) [0.2406]	6.714711E-9 (0.568) [0.5703]	2.724195E-8 (1.864) [0.0624]
1M	3.718536E-10 (0.506) [0.6131]					
34M	1.253540E-9 (1.053) [0.2923]	1.750269E-9 (2.696) [0.0070]	2.007145E-9 (3.120) [0.0018]	1.860166E-9 (2.729) [0.0063]	1.493469E-9 (3.595) [0.0003]	1.112264E-9 (2.702) [0.0069]
58M	-2.231705E-7 (-3.344) [0.0008]	-2.235224E-7 (-3.469) [0.0005]	-1.611324E-7 (-3.428) [0.0006]	-1.581656E-7 (-3.149) [0.0016]	-2.824751E-7 (-6.546) [0.0000]	-2.888512E-7 (-7.600) [0.0000]
12M	2.047589E-7 (1.385) [0.1662]	1.920152E-7 (1.365) [0.1724]			3.648412E-7 (3.716) [0.0002]	4.509314E-7 (4.679) [0.0000]
38M	-1.088391E-6 (-1.914) [0.0556]	-8.837291E-7 (-2.291) [0.0220]	-7.628513E-7 (-1.962) [0.0497]	-9.375310E-7 (-2.339) [0.0193]	-5.631620E-7 (-2.200) [0.0278]	-4.996830E-7 (-2.202) [0.0276]
516M	3.492742E-6 (3.073) [0.0021]	3.125364E-6 (3.704) [0.0002]	3.403923E-6 (4.016) [0.0001]	3.696021E-6 (4.165) [0.0000]	2.102003E-6 (3.578) [0.0003]	1.557812E-6 (2.670) [0.0076]
14M	-2.415139E-6 (-3.895) [0.0001]	-2.241926E-6 (-4.493) [0.0000]	-2.520110E-6 (-5.345) [0.0000]	-2.600291E-6 (-5.183) [0.0000]	-1.675012E-6 (-4.873) [0.0000]	-1.277203E-6 (-3.532) [0.0004]
4M	6.577298E-8 (1.444) [0.1489]	6.912045E-8 (1.588) [0.1123]	7.579290E-8 (1.693) [0.0905]		1.183342E-7 (3.950) [0.0001]	1.134147E-7 (4.294) [0.0000]
Df	10	11	12	13	10	9
N	19	19	19	19	18	17
r^2	0.9397	0.9381	0.9276	0.9104	0.9775	0.9844
$\hat{\sigma}$	0.0162562	0.0156966	0.0162508	0.0173773	0.00993408	0.00871924
r^2_{adj}	0.879	0.883	0.877	0.861	0.957	0.970
Models Compared:		(N1a) – (N1)	(N1b) – (N1a)	(N1c) – (N1b)		
P-value		0.6240	0.1996	0.1163		

$$N1 \quad Y = C^3 * (\alpha + \beta_1 * 1M + \beta_2 * 34M + \beta_3 * 58M + \beta_4 * 12M + \beta_5 * 38M + \beta_6 * 516M + \beta_7 * 14M + \beta_8 * 4M)$$

$$N1a \quad Y = C^3 * (\alpha + \beta_1 * 34M + \beta_2 * 58M + \beta_3 * 12M + \beta_4 * 38M + \beta_5 * 516M + \beta_6 * 14M + \beta_7 * 4M)$$

$$N1b \quad Y = C^3 * (\alpha + \beta_1 * 34M + \beta_2 * 58M + \beta_3 * 38M + \beta_4 * 516M + \beta_5 * 14M + \beta_6 * 4M)$$

$$N1c \quad Y = C^3 * (\alpha + \beta_1 * 34M + \beta_2 * 58M + \beta_3 * 38M + \beta_4 * 516M + \beta_5 * 14M)$$

* Model N1a with case deletion (Shiely Grey Cloud [Larson]).

** Model N1a with case deletions (Shiely Grey Cloud [Larson] and Cedarville Plant).

Table E.13. Multiple linear regression models for response variable “durability factor”
(percentage of mass passing, 19.0 to 37.5 mm [0.75 to 1.5 in]).

Variable	Estimates (t-value) [p-value]		
	Model Number		
	L2	L2a	L2b
α	87.4491 (9.570) [0.0000]	87.5813 (10.034) [0.0000]	86.9953 (10.203) [0.0000]
$1M^{1.06}*C^3$	-1.810613E-6 (-2.281) [0.0457]	-1.794687E-6 (-2.370) [0.0371]	-2.185788E-6 (-4.108) [0.0015]
$34M^{-0.62}*C^3$	-0.000485517 (-2.364) [0.0397]	-0.000484275 (-2.466) [0.0314]	-0.000572332 (-3.733) [0.0029]
$58M^{0.27}*C^3$	0.00119977 (3.399) [0.0068]	0.00119671 (3.545) [0.0046]	0.00101968 (4.364) [0.0009]
$12M^{0.36}*C^3$	-0.000518059 (-0.735) [0.4791]	-0.000494911 (-0.740) [0.4747]	
$38M^{0.65}*C^3$	0.00362540 (2.986) [0.0137]	0.00354124 (3.164) [0.0090]	0.00393516 (4.074) [0.0015]
$516M^{0.73}*C^3$	-0.00797341 (-2.778) [0.0195]	-0.00786667 (-2.895) [0.0146]	-0.00922628 (-4.697) [0.0005]
$14M^{0.84}*C^3$	0.00389911 (2.771) [0.0197]	0.00387102 (2.884) [0.0149]	0.00458659 (5.023) [0.0003]
$4M^{0.41}*C^3$	0.0000225599 (0.260) [0.8004]		
Df	10	11	12
N	19	19	19
r^2	0.795667	0.79429	0.784045
$\hat{\sigma}^2$	19.6509	18.7995	18.4419
r^2_{adj}	0.632	0.663	0.676
Models Compared		(L1) – (L1a)	(L1b) – (L1a)
P-value		0.8005	0.4747
$L^2 Y = \alpha + C^3 * (\beta_1 * 1M^{1.06} + \beta_2 * 34M^{-0.62} + \beta_3 * 58M^{0.27} + \beta_4 * 12M^{0.36} + \beta_5 * 38M^{0.65} + \beta_6 * 516M^{0.73} + \beta_7 * 14M^{0.84} + \beta_8 * 4M^{0.41})$			
$L^{2a} Y = \alpha + C^3 * (\beta_1 * 1M^{1.06} + \beta_2 * 34M^{-0.62} + \beta_3 * 58M^{0.27} + \beta_4 * 12M^{0.36} + \beta_5 * 38M^{0.65} + \beta_6 * 516M^{0.73} + \beta_7 * 14M^{0.84})$			
$L^{2b} Y = \alpha + C^3 * (\beta_1 * 1M^{1.06} + \beta_2 * 34M^{-0.62} + \beta_3 * 58M^{0.27} + \beta_4 * 38M^{0.65} + \beta_5 * 516M^{0.73} + \beta_6 * 14M^{0.84})$			

The models shaded in gray in tables E.12 and E.13 (N1a and L2b) are the final models chosen based on these model checking plots. Figure E.17 illustrates the summary plots for models N1a* and L2b. As illustrated in these figures, there is a strong correlation between the cumulative percentage of mass passing from hydraulic fracture testing and the rapid freezing and thawing test results.

Figure E.17. Actual versus predicted rapid freezing and thawing test results for models N1a* and L2b (percentage of mass passing, 19.0 to 37.5 mm [0.75 to 1.5 in]).

E.4.2 Particle Count Data

E.4.2.1 Explanatory Variables

As stated previously, models were developed to predict percent dilation per 100 cycles of rapid freezing and thawing (dil) and durability factor (DF) as a function of the following explanatory variables:

- 1P: Percentage of particles passing the 25.0-mm (1-in) screen.
- 34P: Percentage of particles passing the 19.0-mm (0.75-in) screen.
- 58P: Percentage of particles passing the 16.0-mm (0.625-in) screen.

12P:	Percentage of particles passing the 12.50-mm (0.5-in) screen.
38P:	Percentage of particles passing the 9.50-mm (0.375-in) screen.
516P:	Percentage of particles passing the 8.00-mm (0.3125-in) screen.
14P:	Percentage of particles passing the 6.35-mm (0.25-in) screen.
4P:	Percentage of particles passing the 4.75-mm (#4) screen.
C:	Percentage of carbonates present in source.

The cumulative percentage of particles passing each specified screen was calculated using the APOPR data presented in table D.10 and defined below:

□ Total Percentage of Original Particles Retained [TPOPR] – *see equation 4.22*

□ Percentage of particles passing the 25.0-mm (1-in) screen [1P]:

$$1P = TPOPR - APOPR_1 \quad (\text{Eqn. E.39})$$

where: TPOPR = Total percentage of original particles retained and

APOPR₁ = average percentage of original particles retained on the 25.0-mm (1-in) screen.

□ Percentage of particles passing the 19.0-mm (0.75-in) screen [34P]:

$$34P = 1P - APOPR_{34} \quad (\text{Eqn. E.40})$$

where: 1P = Percentage of particles passing the 25.0-mm (1-in) screen and

APOPR₃₄ = average percentage of original particles retained on the 19.0-mm (0.75-in) screen.

□ Percentage of particles passing the 16.0-mm (0.625-in) screen [58P]:

$$58P = 34P - APOPR_{58} \quad (\text{Eqn. E.41})$$

where: 34P = Percentage of particles passing the 19.0-mm (0.75-in) screen and

APOPR₅₈ = average percentage of original particles retained on the 16.0-mm (0.625-in) screen.

□ Percentage of particles passing the 12.5-mm (0.5-in) screen [12P] – *see equation E.24*

□ Cumulative percentage of particles passing the 9.50-mm (0.375-in) screen [38P] – *see equation E.25*

□ Percentage of particles passing the 8.00-mm (0.3125-in) screen [516P] – *see equation E.26*

□ Percentage of particles passing the 6.35-mm (0.25-in) screen [14P] – *see equation E.27*

- Percentage of particles passing the 4.75-mm (#4) screen [4P] – *see equation E.28*
- Percentage of particles passing the pan [pan] – *see equation E.29*

The predictors defined by equations E.24 through E.28 and E.39 through E.41 were calculated for each of 19 sources and then transferred as an *lsp* file into *ARC*. Equation E.29 was used as a check to make sure that there were no computational errors.

It should be noted, the TPOPR may be greater than 100 percent due to the fracturing of particles during testing, which may increase the number of particles retained to a number greater than the original number of particles.

E.4.2.2 Transformations to Normality

Two-dimensional scatter plots were developed to show the conditional distributions of the response variables (dilation/100 cycles and durability factor) given changes in each explanatory variable. The scatter plot matrix for the above explanatory and response variables is presented in figure E.18. Normality is achieved when the mean functions are linear and the variance functions are constant (9). As illustrated in figure E.18, there is a lack of normality between the response and explanatory variables in the inverse fitted value plots (marginal distribution plots).

Normality can sometimes be achieved or improved through transformations of the explanatory variables. In this study, explanatory variable transformations were performed using the Box-Cox method (a numerical procedure) in an attempt to improve the linearity of the relationships. Figure E.19 presents the scatter plot matrix for the transformed explanatory variables.

E.4.2.3 Nonlinear and Multiple Linear Regression

As stated previously, past studies have shown that carbonates are typically deleterious in nature. Therefore, the following general nonlinear model form was adopted:

$$E(y|x) = C * (\text{linear combination of } 58P, 12P, 38P, 516P, 14P \text{ and } 4P)$$

therefore,

$$E(y|x) = C * (\alpha + \beta_1 * 58P + \beta_2 * 12P + \beta_3 * 38P + \beta_4 * 516P + \beta_5 * 14P + \beta_6 * 4P) \quad (\text{Eqn. E.42})$$

Figure E.18. Scatter plot matrix for responses and explanatory variables (percentage of particles passing, 19.0 to 37.5 mm [0.75 to 1.5 in]).

Figure E.18. Scatter plot matrix for responses and explanatory variables (percentage of particles passing, 19.0 to 37.5 mm [0.75 to 1.5 in]) (continued).

Figure E.19. Scatter plot matrix for responses and transformed explanatory variables (percentage of particles passing, 19.0 to 37.5 mm [0.75 to 1.5 in]).

Figure E.19. Scatter plot matrix for responses and transformed explanatory variables (percentage of particles, 19.0 to 37.5 mm [0.75 to 1.5 in]) (continued).

Equation E.42 was slightly modified for multiple linear regression to produce basic forms for modeling dilation and durability factor as a function of percentages of mass passing the specified sieves either with or without an interaction term for carbonate content:

$$E(y|x) = \alpha + \beta_1 * C * 38P + \beta_2 * C * 516P + \beta_3 * C * 14P + \beta_4 * C * 4P \quad (\text{Eqn. E.43})$$

$$E(y|x) = \alpha + \beta_1 * 38P + \beta_2 * 516P + \beta_3 * 14P + \beta_4 * 4P \quad (\text{Eqn. E.44})$$

Regression analyses were performed using the model forms presented in equations E.42 through E.44 with both the transformed and untransformed (identity) explanatory variables. Numerous nonlinear and multiple linear regression models were formulated, as discussed previously in section E.2.1.3; however, only the models with the best adjusted R^2 for the response variables, percent dilation per 100 cycles (model N1c) and durability factor (model L2b), were recorded in tables E.14 and E.15, respectively. As described previously, these models were reduced to eliminate predictors that have no significant effect on the mean function. The reduced models are designated with lowercase letters behind the model number (e.g., N1a, N1b, etc.).

E.4.2.4 Model Selection

As described previously, the F-statistic was calculated for each comparison to identify the most compact model that adequately represents the data. As illustrated in tables E.14 and E.15, where all p-values are greater than 0.05, each nested model will adequately represent the data.

Therefore, as described previously, the summary, residual, nonconstant variance and model checking plots were produced to identify the model that most adequately represents the data.

The models shaded in gray in tables E.14 and E.15 are the final models chosen based on these plots. Figure E.20 presents the summary plots for models N1c and L2b. As illustrated in the plots, there is a strong correlation between the hydraulic fracture and freezing and thawing data.

Table E.14. Nonlinear regression models for response variable “percent dilation per 100 cycles” (percentage of particles passing, 19.0 to 37.5 mm [0.75 to 1.5 in]).

Variable	Estimates (Wald-statistic) [p-value]				
	Model Number				
	N1	N1a	N1b	N1c	N1c*
α	-7.845492E-8 (-0.855) [0.3928]	-9.463525E-8 (-1.151) [0.2499]	-1.187643E-7 (-1.713) (0.0867)	-1.434766E-7 (-2.741) [0.0061]	-1.399018E-7 (-3.294) [0.0010]
1P	9.933281E-10 (0.874) [0.3822]	1.226417E-9 (1.240) [0.2151]	1.619587E-9 (2.283) (0.0224)	1.840666E-9 (3.196) [0.0014]	1.747835E-9 (3.733) [0.0002]
34P	8.393640E-10 (0.725) [0.4687]	5.799580E-10 (0.588) [0.5564]			
58P	-3.991039E-8 (-2.179) [0.0293]	-3.870108E-8 (-2.213) [0.0269]	-3.651148E-8 (-2.198) [0.0280]	-2.804111E-8 (-4.025) [0.0001]	-2.661853E-8 (-4.692) [0.0000]
12P	3.282497E-8 (0.796) [0.4262]	2.181416E-8 (0.662) [0.5080]	1.768510E-8 (0.565) [0.5722]		
38P	-5.521042E-8 (-1.752) [0.0798]	-6.300024E-8 (-2.425) [0.0153]	-6.947822E-8 (-3.037) [0.0024]	-7.072665E-8 (-3.190) [0.0014]	-3.945137E-8 (-1.861) [0.0627]
516P	1.166125E-7 (1.587) [0.1124]	1.416649E-7 (2.864) [0.0042]	1.553858E-7 (3.663) [0.0002]	1.733689E-7 (6.353) [0.0000]	1.297791E-7 (4.789) [0.0000]
14P	-6.120006E-8 (-2.812) [0.0049]	-6.310561E-8 (-3.059) [0.0022]	-6.821767E-8 (-3.750) [0.0002]	-7.589939E-8 (-6.454) [0.0000]	-6.512966E-8 (-6.329) [0.0000]
4P	5.524279E-9 (0.477) [0.6337]				
Df	10	11	12	13	12
N	19	19	19	19	18
r^2	0.9194	0.9176	0.9150	0.9127	0.9223
$\hat{\sigma}$	0.0187867	0.0181147	0.0176142	0.0171467	0.0139059
r^2_{adj}	0.839	0.852	0.861	0.869	0.880
Models Compared		(N1) – (N1a)	(N1b) – (N1a)	(N1c) – (N1b)	(N1d) – (N1c)
P-value		0.2270	0.3460	0.3191	0.3573

^{N1} $Y = C^3 * (\alpha + \beta_1 * 1P + \beta_2 * 34P + \beta_3 * 58P + \beta_4 * 12P + \beta_5 * 38P + \beta_6 * 516P + \beta_7 * 14P + \beta_8 * 4P)$
^{N1a} $Y = C^3 * (\alpha + \beta_1 * 1P + \beta_2 * 34P + \beta_3 * 58P + \beta_4 * 12P + \beta_5 * 38P + \beta_6 * 516P + \beta_7 * 14P)$
^{N1b} $Y = C^3 * (\alpha + \beta_1 * 1P + \beta_2 * 58P + \beta_3 * 12P + \beta_4 * 38P + \beta_5 * 516P + \beta_6 * 14P)$
^{N1c} $Y = C^3 * (\alpha + \beta_1 * 1P + \beta_2 * 58P + \beta_3 * 38P + \beta_4 * 516P + \beta_5 * 14P)$

*Model N1c with outlier deleted (Bryan Rock).

Table E.15. Multiple linear regression models for response variable “durability factor” (percentage of particles passing, 19.0 to 37.5 mm [0.75 to 1.5 in]).

Variable	Estimates (t-value) [p-value]			
	Model Number			
	L2	L2a	L2b	L2c
α	121.065 (4.850) [0.0013]	114.796 (5.320) [0.0005]	111.783 (5.764) [0.0002]	122.720 (6.422) [0.0001]
$1P^{0.71}*C^3$	-0.00066517 (-0.656) [0.5299]	-0.000314796 (-0.405) [0.6949]		
$34P^{0.53}*C^3$	-0.0000151755 (-3.380) [0.0096]	-0.0000150618 (-3.490) [0.0068]	-0.0000161437 (-4.976) (0.0006)	-0.0000156374 (-4.573) [0.0008]
$58P^{0.62}*C^3$	0.000351834 (5.669) [0.0005]	0.000344959 (5.889) [0.0002]	0.000336788 (6.398) [0.0001]	0.000353735 (6.486) [0.0001]
$12P^{0.61}*C^3$	-0.000260422 (-2.119) [0.0669]	-0.000278519 (-2.438) [0.0375]	-0.000258172 (-2.629) [0.0252]	-0.000258629 (-2.485) [0.0303]
$38P^{0.58}*C^3$	0.000167750 (1.539) [0.1623]	0.000153817 (1.505) [0.1665]	0.000136889 (1.533) [0.1562]	
$516P^{0.58}*C^3$	-0.000688214 (-3.347) [0.0101]	-0.000631358 (-3.645) [0.0054]	-0.000625218 (-3.785) [0.0036]	-0.000523303 (-3.266) [0.0075]
$14P^{0.55}*C^3$	0.000430044 (4.002) [0.0039]	0.000449355 (4.578) [0.0013]	0.000446406 (4.764) [0.0008]	0.000464517 (4.716) [0.0006]
$4P^{0.5}*C^3$	0.0000452896 (0.573) [0.5825]			
$4P^{0.5}$	-75.1793 (-2.042) [0.0755]	-62.8019 (-2.189) [0.0563]	-60.0509 (-2.251) [0.0481]	-72.6492 (-2.701) [0.0206]
$14P^{0.55}$	56.8302 (2.118) [0.0670]	47.6435 (2.303) [0.0468]	45.7609 (2.371) [0.0392]	54.5577 (2.794) [0.0175]
df	8	9	10	11
N	19	19	19	19
r^2	0.951469	0.949478	0.948558	0.936462
$\hat{\sigma}$	10.7072	10.2999	9.85995	10.448
r^2_{adj}	0.891	0.899	0.907	0.896
Models Compared		(L1) – (L1a)	(L1b) – (L1a)	(L1c) – (L1b)
P-value		0.5825	0.9490	0.1562
$L^2Y = \alpha + C^3*(\beta_1*1P^{0.71} + \beta_2*34P^{0.53} + \beta_3*58P^{0.62} + \beta_4*12P^{0.61} + \beta_5*38P^{0.58} + \beta_6*516P^{0.58} + \beta_7*14P^{0.55} + \beta_8*4P^{0.5}) + \beta_9*4P^{0.5} + \beta_{10}*14P^{0.55}$				
$L^{2a}Y = \alpha + C^3*(\beta_1*1P^{0.71} + \beta_2*34P^{0.53} + \beta_3*58P^{0.62} + \beta_4*12P^{0.61} + \beta_5*38P^{0.58} + \beta_6*516P^{0.58} + \beta_7*14P^{0.55}) + \beta_8*4P^{0.5} + \beta_9*14P^{0.55}$				
$L^{2b}Y = \alpha + C^3*(\beta_1*34P^{0.53} + \beta_2*58P^{0.62} + \beta_3*12P^{0.61} + \beta_4*38P^{0.58} + \beta_5*516P^{0.58} + \beta_6*14P^{0.55}) + \beta_7*4P^{0.5} + \beta_8*14P^{0.55}$				
$L^{2c}Y = \alpha + C^3*(\beta_1*34P^{0.53} + \beta_2*58P^{0.62} + \beta_3*12P^{0.61} + \beta_4*516P^{0.58} + \beta_5*14P^{0.55}) + \beta_6*4P^{0.5} + \beta_7*14P^{0.55}$				

However, the correlation is not as strong as that achieved with the mass data obtained for this size fraction.

Figure E.20. Actual versus predicted rapid freezing and thawing results for models N1c and L2b (percentage of particles passing, 19.0 to 37.5 mm [0.75 to 1.5 in]).

E.5 Final Model Selection

E.5.1 Summary of Models

Table E.16 lists the regression models selected for each initial size fraction. In general, the correlation between the hydraulic fracture test results (i.e., percentage of mass or particles passing selected sieves) and rapid freezing and thawing test results (i.e., percent dilation per 100 cycles or durability factor) increases with increased particle sizes incorporated in the initial size fraction. These results support the findings of previous research, where it was found that the greatest amount of freeze-thaw damage occurred with larger size particles due to the greater hydraulic pressures generated due to the greater escape distances (12).

Table E.16. Summary of regression analysis models.

Initial Size Fraction (mm)	Explanatory Variable (cumulative percentage passing)	R ²	Adj. R ²	General Equation	Table No.*
Percentage of Dilation per 100 Cycles of Rapid Freezing and Thawing					
4.75 to 12.5	Mass	0.334	0.256	^{L1b} $Y = \alpha + C^{2.33} * (\beta_1 * 38M^2 + \beta_2 * 14M^{0.31})$	E.6
12.5 to 19.0	Mass	0.768	0.661	^{N1a} $Y = C^2 * (\alpha + \beta_1 * 58M + \beta_2 * 12M + \beta_3 * 38M + \beta_4 * 516M + \beta_5 * 14M)$	E.8
	Particles	0.806	0.717	^{N1a} $Y = C^{1.9} * (\alpha + \beta_1 * 58P^{0.2} + \beta_2 * 12P^{0.67} + \beta_3 * 38P^{0.61} + \beta_4 * 516P^{0.58} + \beta_5 * 14P^{0.5})$	E.10
19.0 to 37.5	Mass	0.978	0.957	^{N1a*} $Y = C^3 * (\alpha + \beta_1 * 34M + \beta_2 * 58M + \beta_3 * 12M + \beta_4 * 38M + \beta_5 * 516M + \beta_6 * 14M + \beta_7 * 4M)$	E.12
	Particles	0.913	0.869	^{N1c} $Y = C^3 * (\alpha + \beta_1 * 1P + \beta_2 * 58P + \beta_3 * 38P + \beta_4 * 516P + \beta_5 * 14P)$	E.14
Durability Factor					
4.75 to 12.5	Mass	0.395	0.284	^{L2a} $Y = \alpha + C^{2.33} * (\beta_1 * 38M^2 + \beta_2 * 516M + \beta_3 * 14M^{0.31})$	E.7
12.5 to 19.0	Mass	0.666	0.547	^{L2a} $Y = \alpha + C * (\beta_1 * 58M + \beta_2 * 12M + \beta_3 * 38M + \beta_4 * 516M + \beta_5 * 14M)$	E.9
	Particles	0.734	0.611	^{L2f} $Y = \alpha + C * (\beta_1 * 38P^{0.61} + \beta_2 * 516P^{0.58}) + \beta_3 * 14P^{0.5} + \beta_4 * 38P^{0.61} + \beta_5 * 12P^{0.67} + \beta_6 * 58P^{0.2}$	E.11
19.0 to 37.5	Mass	0.784	0.676	^{L2b} $Y = \alpha + C^3 * (\beta_1 * 1M^{1.06} + \beta_2 * 34M^{-0.62} + \beta_3 * 58M^{0.27} + \beta_4 * 38M^{0.65} + \beta_5 * 516M^{0.73} + \beta_6 * 14M^{0.84})$	E.13
	Particles	0.949	0.907	^{L2b} $Y = \alpha + C^3 * (\beta_1 * 34P^{0.53} + \beta_2 * 58P^{0.62} + \beta_3 * 12P^{0.61} + \beta_4 * 38P^{0.58} + \beta_5 * 516P^{0.58} + \beta_6 * 14P^{0.55}) + \beta_7 * 4P^{0.5} + \beta_8 * 14P^{0.55}$	E.15

*Coefficient estimates are listed in designated table.

E.5.2 Final Model

Model N1a* representing percent dilation per 100 cycles of rapid freezing and thawing as a function of the percentages of mass passing the designated sieves when testing the initial size fraction of 19.0 to 37.5 mm (0.75 to 1.5 in) was the model identified as best representing the project test data. This model is defined as follows:

Model N1a*:

$$\% \text{ Dil}/100 = C^3*(6.714711E-9 + 1.493469E-9*34M - 2.824751E-7*58M + 3.648412E-7*12M - 5.631620E-7*38M + 2.102003E-6*516M - 1.675012E-6*14M + 1.183342E-7*4M)$$

(Eqn. E.45)

$$R^2 = 0.978, \text{ Adjusted } R^2 = 0.957, \hat{\sigma} = 0.009934, n = 18$$

As illustrated in table E.12, the explanatory variables used in model N1a* are the same as those used in model N1a; however, the outlier Shiely Grey Cloud [Larson] (Case 13) was omitted from the regression analysis for model N1a*.

Figure E.21 presents the summary, nonconstant variance and residual plots for model N1a, where case 13 was not deleted. Case 13 is highlighted in each plot to illustrate the location of this outlier with respect to the other data points. Figure E.22 presents the final summary, nonconstant variance and residual plots for model N1a* with the outlier (case 13) deleted. As illustrated in these plots, the removal of the outlier greatly improves the correlation of the hydraulic fracture data with the response (i.e., percentage of dilation per 100 cycles).

a. Response versus fit-values.

b. Nonconstant variance plot.

c. Residuals versus 34M.

d. Residuals versus 58M.

Figure E.21. Graphs (a – j) illustrating outlier (case 13, Shiely Grey Cloud [Larson]) in model N1a (percentage of mass passing, 19.0 to 37.5 mm [0.75 to 1.5 in]).

e. Residuals versus 12M.

f. Residuals versus 38M.

g. Residuals versus 516M.

h. Residuals versus 14M.

Figure E.21. Graphs (a – j) illustrating outlier (case 13, Shiely Grey Cloud [Larson]) in model N1a (percentage of mass passing, 19.0 to 37.5 mm [0.75 to 1.5 in]) (continued).

i. Residuals versus 4M.

j. Residuals versus C^3 .

Figure E.21. Graphs (a – j) illustrating outlier (case 13, Shiely Grey Cloud [Larson]) in model N1a (percentage of mass passing, 19.0 to 37.5 mm [0.75 to 1.5 in]) (continued).

a. Response versus fit-values.

b. Nonconstant variance plot.

Figure E.22. Graphs (a – j) illustrating model N1a* with deleted outlier (case 13, Shiely Grey Cloud [Larson]) (percentage of mass passing, 19.0 to 37.5 mm [0.75 to 1.5 in]).

c. Residuals versus 34M.

d. Residuals versus 58M.

e. Residuals versus 12M.

f. Residuals versus 38M.

Figure E.22. Graphs (a – j) illustrating model N1a* with deleted outlier (case 13, Shiely Grey Cloud [Larson]) (percentage of mass passing, 19.0 to 37.5 mm [0.75 to 1.5 in]) (continued).

g. Residuals versus 516M.

h. Residuals versus 14M.

i. Residuals versus 4M.

j. Residuals versus C^3 .

Figure E.22. Graphs (a – j) illustrating model N1a* with deleted outlier (case 13, Shielly Grey Cloud [Larson]) (percentage of mass passing, 19.0 to 37.5 mm [0.75 to 1.5 in]) (continued).