Minnesota
Department of
Transportation

RESEARCH
SERVICES

Office of
Policy Analysis,
Research &
Innovation

Concrete Delivery Time Study

Daniel M. Vruno, Primary Author
American Engineering Testing, Inc.

November 2011

Research Project
Final Report 2011-26

LRRB
LOCAL
ROAD RESEARCH
BOARD

Your Destination...Our Priority

All agencies, departments, divisions and units that develop, use and/or purchase written materials for distribution to the public must ensure that each document contain a statement indicating that the information is available in alternative formats to individuals with disabilities upon request. Include the following statement on each document that is distributed:

To request this document in an alternative format, call Bruce Lattu at 651-366-4718 or 1-800-657-3774 (Greater Minnesota); 711 or 1-800-627-3529 (Minnesota Relay). You may also send an e-mail to bruce.lattu@state.mn.us. (Please request at least one week in advance).

Technical Report Documentation Page

1. Report No.	2.	3. Recipients Accession No.
MN/RC 2011-26		

4. Title and Subtitle	5. Report Date
Concrete Delivery Time Study	November 2011
	6.
7. Author(s) Daniel Vruno	8. Performing Organization Report No.
9. Performing Organization Name and Address American Engineering Testing, Inc. 550 Cleveland Avenue North St. Paul, MN 55114	10. Project/Task/Work Unit No. 11. Contract (C) or Grant (G) No. (c) 96033
12. Sponsoring Organization Name and Address Minnesota Department of Transportation Research Services Section 395 John Ireland Boulevard, MS 330 St. Paul, MN 55455	13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code

15. Supplementary Notes
http://www.lrrb.org/pdf/201126.pdf

16. Abstract (Limit: 250 words)

The MnDOT Concrete Transit Time Study is intended to evaluate the influence of concrete delivery time by measuring material properties from laboratory-batched concrete with different materials and admixtures. The laboratory test results will be used to develop a field testing and evaluation program. The field portion of the study will evaluate materials and admixture from ready mix plants in each region of the state. This will aid in the determination of whether there are any regional issues that need to be taken into account if the transit time specification is lengthened.

17. Document Analysis/Descriptors	18. Availability Statement
Extended transit time, Travel time, Durability, Supplementary cementitious materials, SCM, Cement, Replacement, Air, Air content, Hardened air, Slump test, Slump loss, Air loss	No restrictions. Document available from: National Technical Information Services, Alexandria, Virginia 22312

19. Security Class (this report)	20. Security Class (this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	177	

Concrete Delivery Time Study

Final Report

Prepared by:

Daniel M. Vruno

American Engineering Testing, Inc.

November 2011

Published by:

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

ACKNOWLEDGMENTS

This work was sponsored by the Minnesota Department of Transportation (MnDOT). The author gratefully acknowledges the support of the agency and the cooperation and assistance of its personnel, especially: Ms. Maria Masten, Mr. Gordon Bruhn, Mr. Bernard Izevbekhai, Mr. Ron Mulvaney, Ms. Wendy Garr, Ms. Shirlee Sherkow, Mr. Rob Golish, Ms. Ally Akkari, and Mr. Curt Turgeon.

The author would also like to thank the following persons and agencies for their assistance in compiling and analyzing the information summarized in this report: Mr. Darrell Stahlecker of Biesanz Stone; Mr. Joe Clendenen of Holcim; Mr. Tom Rogers of Knife River; Mr. Josh Edwards of AVR, Inc.; Mr. Matt Zeller of CPAM; Mr. Fred Corrigan of Aggregate Ready Mix of Minnesota; Mr. Mike Malherek of W.R. Grace; Mr. Justin Lashley of Lafarge; Mr. Tom Schmit of Aggregate Industries; Mr. Mark Bintzler of Aggregate Industries; Mr. Scott Baril of Brett Admixtures; Mr. Mark Johnson of BASF Admixtures, Inc.; Mr. Mark Snyder, Consultant; and Mr. Richard Kohn of Sika Corporation.

TABLE OF CONTENTS

CHAPTER 1. INTRODUCTION 1
1.1 Project Objectives 1
CHAPTER 2. LABORATORY TESTING PROGRAM 2
Task 1 2
2.1 Background 2
2.2 Laboratory Test Program 2
2.3 Laboratory Mixing Test Results 5
2.4 Hardened Concrete Test Results 10
2.5 Freeze-Thaw Test Results 13
CHAPTER 3. CONTROLLED PLANT MIXING PROGRAM 14
Task 2 14
3.1 Background 14
3.2 Controlled Plant Mixing Program Test Results 17
3.3 Hardened Concrete Test Results 18
3.4 Freeze-Thaw Results 19
CHAPTER 4. REGIONAL TESTING 20
Task 3 20
4.1 Background 20
4.2 Regional Testing Program 21
4.3 Regional Testing Program Test Results 22
4.4 Hardened Concrete Test Results 23
4.5 Freeze-Thaw Test Results 25
CHAPTER 5. STATISTICAL ANALYSIS 26
5.1 Statistical Analysis Approach #1 26
5.1.1 Paired students T-Test, 95% Confidence 26
5.2 Statistical Analysis Approach #2 31
5.2.1 Task 1 31
5.2.2 Task 2 37
5.2.3 Task 3 39
CHAPTER 6. CALORIMETRY TESTING 42
6.1 Background 42
6.2 Procedure 42
6.3 Observations 43
CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS 44
7.1 Background 44
7.2 Conclusions 44
7.3 Recommendations 44
Appendix A: Task 1 – Laboratory Test Result
Appendix B: Task 2 – Controlled Plant Mixing Program Test Results
Appendix C: Task 3 – Regional Concrete Testing Results
Appendix D: Hardened Air Contents
Appendix E: Statistical Analysis Raw Data
Appendix F: Thermo Calorimetry Graphs
Appendix G: Isothermal Calorimetry Graphs

LIST OF TABLES

Table 1. Cementitious Materials and Admixtures ... 5
Table 2. Initial Unit Weight/Temperature ... 6
Table 3. Plastic Air Content Measurements (%) ... 7
Table 4. Slump Measurements (inch) ... 9
Table 5. Hardened Air (%) ... 10
Table 6. Compressive Strength (psi) ... 11
Table 7. Mix Design Specifications ... 14
Table 8. Cementitious Materials and Admixtures ... 14
Table 9. Plastic Air Content Measurements (%) ... 17
Table 10. Slump Measurements (inches) ... 17
Table 11. Hardened Air (%) ... 18
Table 12. Compressive Strength Results, psi ... 19
Table 13. Cementitious Materials and Admixtures ... 20
Table 14. Plastic Air Content Measurement (%) ... 22
Table 15. Slump Measurements (inches) ... 23
Table 16. Hardened Air (%) ... 23
Table 17. Compressive Strength Results (psi) ... 24
Table 18. Change in Air (%) ... 27
Table 19. Change in Slump (in) ... 27
Table 20. Compressive Strength – Task 1 ... 28
Table 21. Compressive Strength – Task 3 ... 28
Table 22. Change in Delivery Time ... 28
Table 23. Wilcoxon Signed Rank Test – Slump and Air ... 30
Table 24. Wilcoxon Signed Rank Test – Durability and Hardened Air ... 30
Table 25. Wilcoxon Signed Rank Test – Compressive Strength ... 31
Table 26. Summary of Gross Averages for Batches 1-8 ... 33
Table 27. Summary of Gross Averages for Batches #5-12, 15, 16, 18, and 19 ... 34
Table 28. Summary of Gross Averages for Batches 13-16 ... 35
Table 29. Summary of Gross Averages for Batches #17, 18, 20 and 21 ... 36
Table 30. Summary of Gross Test Result Averages for Task 2 ... 38
Table 31. Summary of Gross Test Result Averages for Task 3 ... 40

LIST OF FIGURES

Figure 1. Laboratory Testing 3
Figure 2. Average Air vs. Time since Mixing 8
Figure 3. Average Slump vs. Time Since Mixing 10
Figure 4. Plastic Air vs. Hardened Air 11
Figure 5. Concrete Compressive Strength 13
Figure 6. Controlled Plant Testing 15
Figure 7. Plastic Air vs. Hardened Air 18
Figure 8. Compressive Strength 19
Figure 9. Regional Testing 21
Figure 10. Plastic Air vs. Hardened Air 24

EXECUTIVE SUMMARY

The concrete industry has been asking the Minnesota Department of Transportation (MnDOT) to lengthen the time allowed to deliver concrete. MnDOT is planning on constructing many small bridge projects that are difficult to reach within the existing 60-minute time limit for air-entrained concrete. This 60-minute time limit could unnecessarily increase the cost to construct these bridges. Although other state DOTs do allow longer transit times with the use of retarding admixtures, there are no known studies to verify whether the longer hauling time is detrimental to concrete performance. Also, there may be significant differences in the mix designs and materials that are used by other state DOTs, as well as the environments that the concrete is placed and expected to perform in.

The goal of this project was to utilize the results of the testing programs and develop specification guidelines that allow the implementation of chemical admixtures to extend transport and delivery time from the current 60 minutes for air-entrained concrete up to 120 minutes.

A total of 41 concrete batches were performed. This study consisted of three tasks. Task 1 began by batching 23 concrete mixtures using the same mix design, but with various kinds and combinations of cement, fly ash, water reducer, water-reducing retarder, hydration stabilizer, and air-entrainment admixtures. The plastic concrete properties were tested initially and then after 30, 60, 90, and 120 minutes. Hardened concrete proportions such as compressive strength, freeze-thaw, and hardened airs were also performed on concrete that was originally cast after initial mixing and at 120 minutes.

Task 2 consisted of conducting a controlled plan mixing program at a single ready mix concrete plant. This task was intended to evaluate the two concrete mixes (3A32 and 3Y43) that would be used in Task 3. The plastic concrete properties were tested initially and then after 30, 60, 90, and 120 minutes. Hardened concrete properties such as compressive strength, freeze-thaw, and hardened airs were also performed on concrete that was originally cast at 60 and 120 minutes after initial mixing.

Task 3 was a regional testing program consisting of seven ready mix plants located throughout Minnesota. The plastic and hardened concrete testing was performed as described in Task 2. An additional aspect of this study was the use of calorimetry to study the performance of various combinations of cement, fly ash, and admixtures.

The data obtained by each of the three tasks was analyzed statistically. Two approaches for statistical analysis were performed. The statistical evaluation showed the following:

- There is a drop in plastic and hardened air content when extending the transit time from 60 minutes to 120 minutes; 1.3 percent and 1.2 percent, respectively.
- There is a significant loss of slump with an average loss of 1.7 inches.
- There was not a significant effect on concrete compressive strength by extending the transit time.
- There was not a significant effect on freeze-thaw durability by extending the transit time.

As a result of this research, specification guidelines were developed that allows the implementation of chemical admixtures to extend transport and delivery time from the current 60 minutes for air-entrained concrete up to 120 minutes.

CHAPTER 1. INTRODUCTION

1.1 Project Objectives

The concrete industry has been asking the Minnesota Department of Transportation (MnDOT) to lengthen the time allowed to deliver concrete. MnDOT is planning on constructing many small bridge projects that are difficult to reach within the existing 60-minute time limit for air-entrained concrete. This 60-minute time limit may unnecessarily increase the cost to construct these bridges. Although other state DOTs do allow longer transit times with the use of retarding admixtures, there are no known studies to verify whether the longer hauling time is not detrimental to concrete performance. Also, there may be significant differences in the mix designs and materials that are used by other state DOTs, as well as the environments that the concrete is placed and expected to perform in.

This study consisted of three tasks. Task 1 began by batching twenty-three concrete mixtures using the same mix design, but with various kinds and combinations of cement, fly ash, water reducer, water-reducing retarder, hydration stabilizer, and air-entrainment admixtures. The plastic concrete properties were tested initially and then after 30, 60, 90, and 120 minutes. Hardened concrete proportions such as compressive strength, freeze-thaw, and hardened airs were also performed on concrete that was cast after initial mixing and at 120 minutes.

Task 2 consisted of conducting a controlled plan mixing program at a single ready mix concrete plant. This task was intended to evaluate the two concrete mixes (3A32 and 3Y43) that would be used in Task 3. The plastic concrete properties were tested initially and then after 30, 60, 90, and 120 minutes. Hardened concrete properties such as compressive strength, freeze-thaw, and hardened airs were also performed on concrete that was originally cast at 60 and 120 minutes after initial mixing.

Task 3 was a regional testing program consisting of seven ready mix plants which were located throughout Minnesota. The plastic and hardened concrete testing was performed as described in Task 2. An additional aspect of this study was the use of calorimetry to study the performance of various combinations of cement, fly ash, and admixtures.

Concrete from the Knife River Baxter Plant and the Aggregate Industries Minneapolis Plant were placed as walkways after the 120 minute testing was performed. These two placements provide us with potential “real world” long term performance studies.

Finally, the data obtained by each of the three tasks was analyzed statistically. Two approaches for statistical analysis were performed. These analyses were valuable in the formation of our conclusions.

CHAPTER 2. LABORATORY TESTING PROGRAM

Task 1

2.1 Background

The laboratory testing program was developed by the project technical working group consisting of Maria Masten (MnDOT), Dan Vruno, American Engineering Testing, Inc. (AET), and Darrell Stahlecker, formerly of General Resource Technology (GRT). The program was limited by budget to 23 mixes. Cement, fly ash and admixture combinations were selected after contacting ready-mix suppliers and determining materials combinations that are being used in current practice. While it was apparent that this approach would not result in a testing matrix that would allow for a complete statistical evaluation, it did match current practice in Minnesota, and did not require the evaluation of materials combinations that would not occur (due to cement/fly ash supply limitations or admixture availability) just for statistical completeness.

The intent of the laboratory mixing study is to allow the evaluation of the admixtures, cementitious material combinations, and dosage rates for the field testing program. It was also intended to allow for screening of any combinations that did not provide adequate plastic or hardened concrete properties so that those combinations could either be adjusted in the lab and reevaluated or eliminated from the field testing program.

2.2 Laboratory Test Program

The final testing program consisted of the following as shown in Figure 1.

- Lab Test Matrix
  - 23 mixes
  - 7 air entraining admixtures (2 vinsol resins, 2 vinsol rosin, 3 synthetics)
  - 3 portland cements
  - 3 fly ashes
  - 7 retarding water reducers
  - 4 mid-range water reducers

The three most used cements and fly ashes in Minnesota were chosen for the study. The chemical admixtures were suggested by four admixture companies based on potential success for eventual field applications.

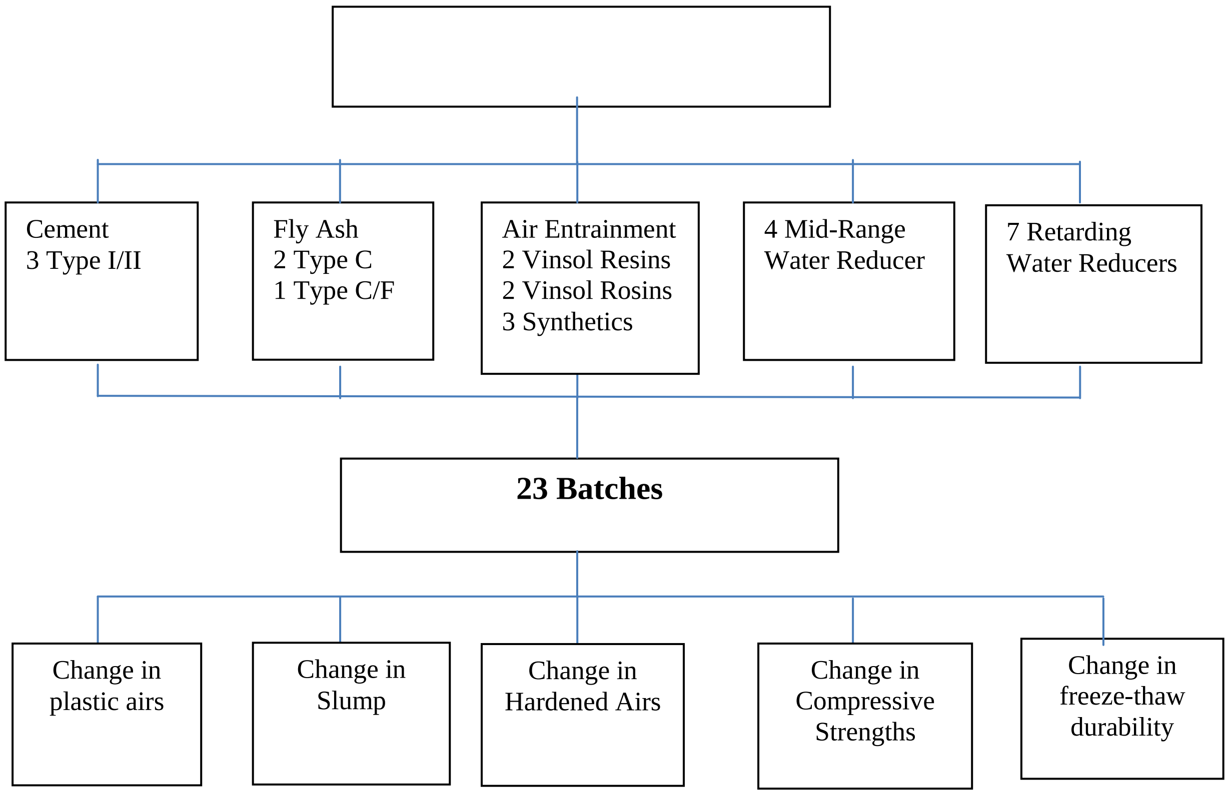


Figure 1. Laboratory Testing

<u>Mix Proportions (SSD)</u>

<u>Batch #1-23</u>	**<u>Design</u>**
Cement, pcy	414
Fly Ash, pcy	103 (20%)
3/4" Gravel, pcy	1,818
Concrete Sand, pcy	1,331
Water, pcy	223
Water Cementitious Ratio	.43

The mix was designed by the project technical working group to obtain a 28-day compressive strength of 4,500 psi.

The adjusted mix proportions for each batch are shown in Table A1 in Appendix A.

The batching was performed in June 2010, the procedure is described below:

- Batching Procedure
    - Moistures were performed on aggregates prior to batching. Aggregate weights and batch water were adjusted accordingly.
    - Sand and rock were added to mixer and mixed.
    - Batch water was split up into three buckets. Individual admixtures were added to separate buckets.
    - Batch water with admixtures were added to mixer and mixed.
    - Cement and fly ash were added to the mixer and mixed. This is considered initial time of batch.
    - Initial plastic testing was then performed.
    - Initial hardened samples were cast.
    - The remaining concrete was placed in plastic buckets and covered with moist burlene.
    - Plastic tests were performed at 30 and 60 minutes.
    - Concrete was placed back in mixer at 87 minutes and mixed for 3 minutes.
    - Plastic tests were performed at 90 minutes.
    - Concrete was placed back in plastic buckets and covered with moist burlene.
    - Plastic tests were performed at 120 minutes.
    - Final hardened samples were cast.

The plastic concrete was tested with the following procedures:

The slump was measured in accordance with ASTM:C143, "Standard Test Method for Slump of Portland Cement Concrete." The air content of the concrete was tested by the pressure method according to ASTM:C231, "Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method." Unit weight was determined in accordance with ASTM:C138, "Standard Test Method for Unit Weight, Yield and Air Content (Gravimetric) of Concrete."

The hardened concrete was tested with the following procedures:

The compressive strength samples were standard 4 inch x 8 inch cylinders. The cylinders were tested in accordance with ASTM:C39, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens." The freeze-thaw testing was performed in accordance with ASTM:C666 Method A, “Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing.” Hardened air was determined in accordance with ASTM:C457, “Linear Transverse Method.”

The cementitious materials and admixture combinations are shown in Table 1 below:

Table 1. Cementitious Materials and Admixtures

Batch No.	Cement	Fly Ash	Air Entrainment	Mid-Range Water Reducer	Retarder Water Reducer
1	2	1	Vinsol Resin #1	-	#2
2	2	2	Vinsol Resin #1	-	#2
3	2	1	Synthetic #1	-	#2
4	2	2	Synthetic #1	-	#2
5	1	1	Vinsol Resin #1	-	#3
6	1	2	Vinsol Resin #1	-	#3
7	1	1	Synthetic #1	-	#3
8	1	2	Synthetic #1	-	#3
9	1	1	Vinsol Resin #2	-	#4
10	1	2	Vinsol Resin #2	-	#4
11	1	1	Vinsol Rosin #1	#1	#1
12	1	2	Vinsol Rosin #1	#1	#1
13	3	1	Synthetic #2	#2	#6
14	3	2	Synthetic #2	#2	#6
15	1	1	Synthetic #2	#2	#6
16	1	2	Synthetic #2	#2	#6
17	1	3	Synthetic #3	#3	#7
18	1	1	Synthetic #3	#3	#7
19	1	2	Synthetic #3	#3	#7
20	1	1	Vinsol Rosin #2	-	#5
21	1	3	Vinsol Rosin #2	-	#5
22	2	1	Vinsol Rosin #2	#4	#5
23	2	3	Vinsol Rosin #2	#4	#5

2.3 Laboratory Mixing Test Results

The plastic mix properties are shown in Tables 2, 3 and 4 below. The concrete materials were mixed at approximately 70^{O}F. The unit weight of the mixes ranged from 141.6 to 144.8 lbs/yd^3 due to variations in air content and aggregate specific gravity.

Table 2. Initial Unit Weight/Temperature

Ambient Laboratory Temperature, 70° F

Batch No.	Initial Unit Weight, pcy	Initial Concrete Temp, °F
1	144.8	68
2	144.4	68
3	144.8	69
4	144.9	69
5	144.8	69
6	144.4	70
7	144.7	69
8	144.9	70
9	144.4	73
10	144.4	70
11	144.8	69
12	144.4	70
13	142.4	66
14	142.0	67
15	141.6	67
16	142.0	67
17	142.8	77
18	141.4	77
19	141.2	77
20	141.6	75
21	144.8	75
22	141.6	75
23	142.8	75

It can be seen in Table 3 and Figure 2 that the air content changed significantly between the initial measurement after mixing and at 60 minutes – dropping by an average of 2.3%. It can also be seen that after remixing at 90 minutes the air content in the majority of the mixes increased by an average of 0.8%. Between 90 minutes and 120 minutes the air content dropped by an average of 0.5%.

Table 3. Plastic Air Content Measurements (%)

Batch No.	Initial	30 min.	60 min.	90 min.	120 min
1	7.2	6.0	5.3	5.8	5.2
2	7.4	5.9	5.3	5.7	4.9
3	7.1	5.1	4.5	5.2	4.9
4	5.9	4.9	4.2	4.7	4.2
5	7.1	5.5	5.4	5.7	4.8
6	8.0	6.1	6.0	5.3	5.0
7	7.0	4.6	4.2	5.5	4.8
8	6.2	4.2	4.0	4.9	4.2
9	6.0	3.8	3.0	6.5	6.1
10	6.9	3.7	3.4	6.3	5.6
11	6.2	3.4	3.3	7.4	7.0
12	7.0	4.4	3.5	6.0	5.8
13	7.6	6.7	5.8	6.0	5.0
14	7.8	6.8	5.7	5.3	5.5
15	8.1	6.0	5.5	5.8	5.8
16	8.0	6.6	5.8	6.0	5.8
17	7.4	5.3	4.7	4.7	4.4
18	9.3	7.8	6.8	6.2	5.7
19	9.5	8.0	7.0	6.2	6.2
20	7.8	6.2	5.3	6.0	5.2
21	5.5	5.0	4.6	5.5	5.4
22	8.0	6.6	5.6	5.8	5.6
23	7.6	6.0	5.6	6.2	5.5
Average	**7.3**	**5.6**	**5.0**	**5.8**	**5.3**

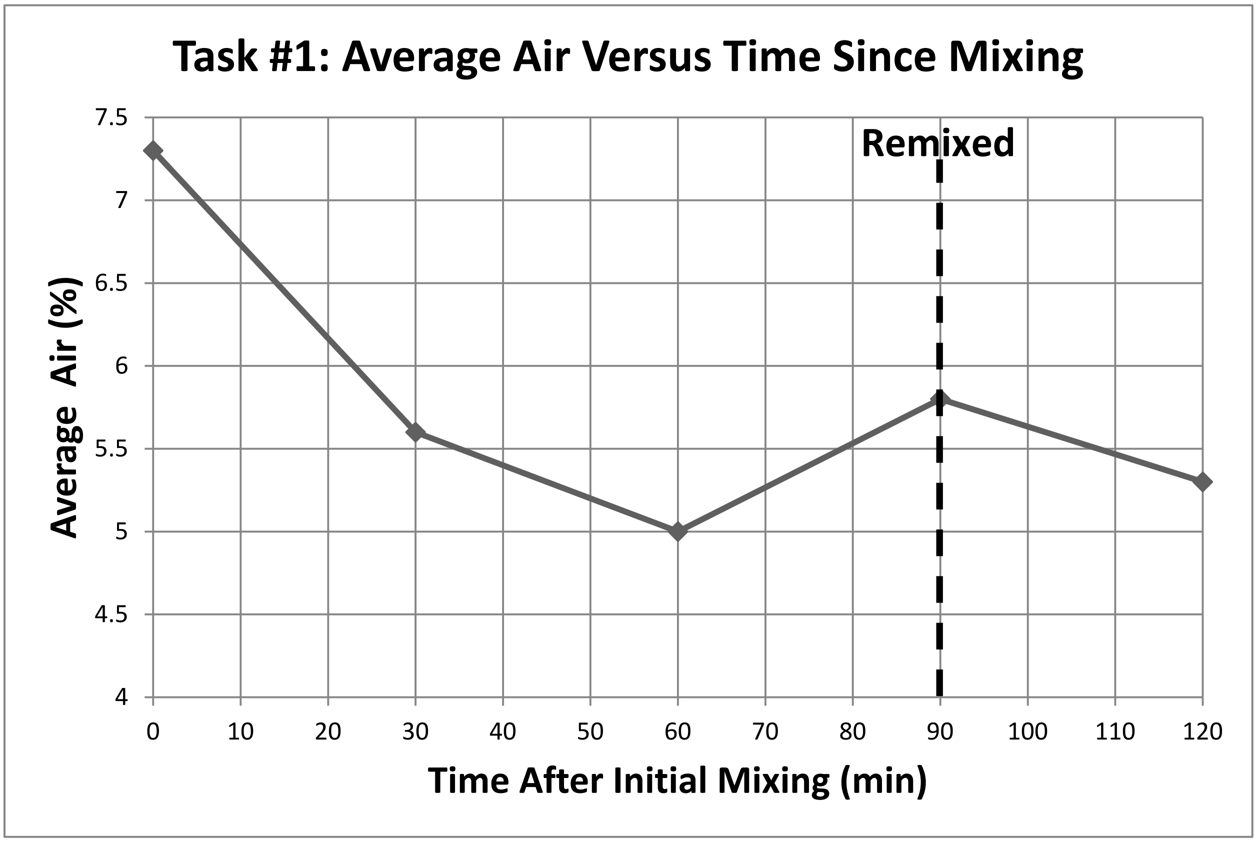


Figure 2. Average Air vs. Time since Mixing

Table 4 and Figure 3 show the change in slump with time. As with the air content, there were significant changes in the slump after mixing. From the initial slump tests after mixing to those taken at 60 minutes, the slump measurements dropped by an average of 4.19 inches. After remixing at 90 minutes, the slump increased by an average of 0.89 inches. Between 90 and 120 minutes the slump dropped by an average of 0.55 inches.

Table 4. Slump Measurements (inch)

Batch No.	Initial	30 min.	60 min.	90 min.	120 min
1	3.75	3.25	1.50	4.5	3.50
2	5.50	1.50	1.25	2.75	2.50
3	5.50	2.50	2.00	2.50	2.50
4	6.50	2.75	2.00	2.50	0.25
5	6.75	2.75	2.75	3.25	2.25
6	8.00	5.25	4.50	3.50	2.75
7	8.75	6.50	4.50	5.50	4.50
8	8.00	6.25	4.00	5.25	4.25
9	6.50	1.50	2.00	4.75	4.00
10	7.00	2.50	1.75	3.25	2.75
11	5.75	2.25	2.00	5.00	4.00
12	5.75	1.50	1.75	3.50	2.50
13	6.00	4.50	2.50	6.00	3.25
14	6.50	4.75	1.75	2.75	2.75
15	7.50	3.50	2.50	2.50	2.25
16	7.75	4.50	2.50	3.75	2.75
17	6.50	2.00	1.25	2.00	1.50
18	7.50	2.75	2.25	2.50	2.00
19	7.75	3.00	2.75	2.75	2.00
20	7.00	4.00	4.00	4.00	4.50
21	4.75	1.50	1.25	2.00	2.25
22	6.50	1.75	2.50	2.50	1.75
23	6.50	2.75	2.50	2.75	2.75
Average	**6.61**	**3.20**	**2.42**	**3.31**	**2.76**

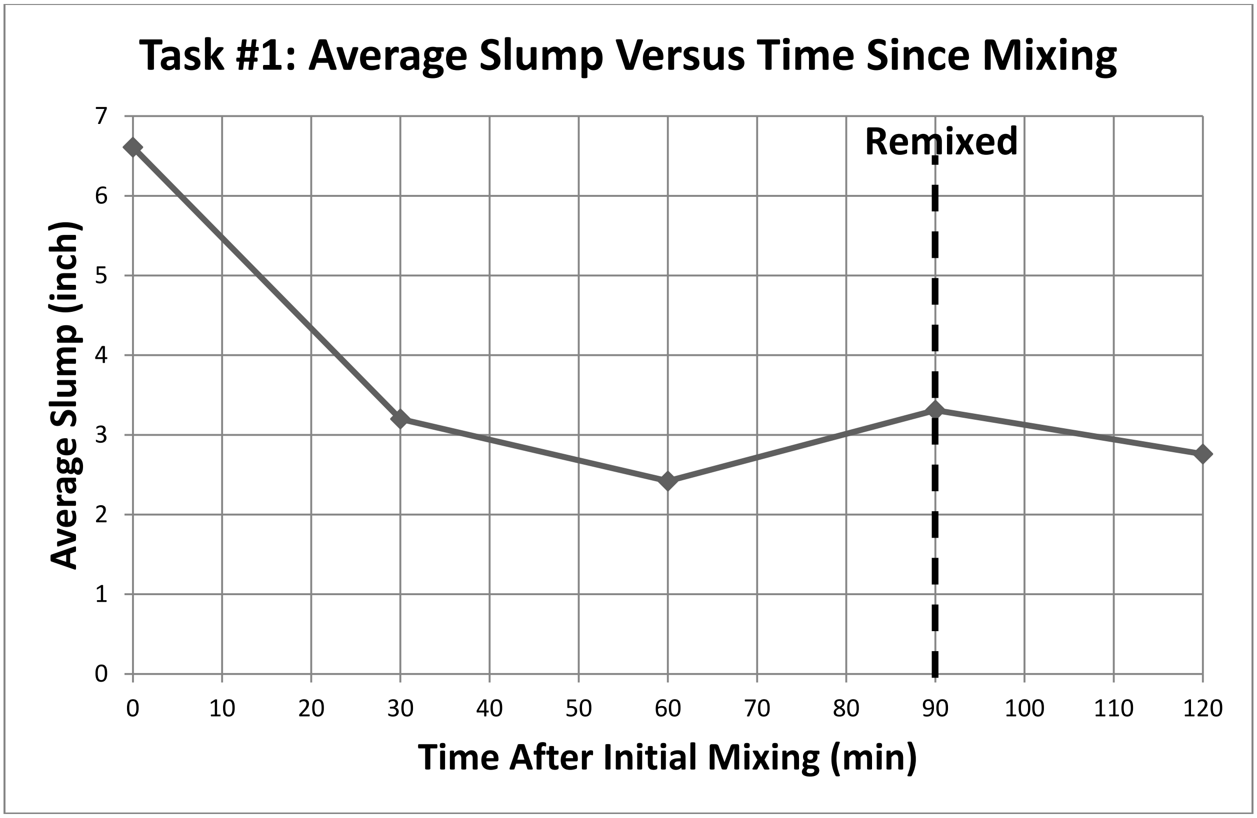


Figure 3. Average Slump vs. Time since Mixing

2.4 Hardened Concrete Test Results

After curing for 7 days, 14 samples were tested for air hardened air content (two samples were cast after initial mixing and two were cast after 120 minutes). It can be seen from the results shown in Table 5 and Figure 4 that there was a slight drop in the hardened air content (0.4%) between the samples taken after mixing and those taken after 120 minutes. It can also be seen that there are significant differences in the plastic and hardened air contents of the mixes. The plastic airs are given in (parenthesis) for convenience.

Table 5. Hardened Air (%)

Batch No.	Initial	120 min
1	4.2 (7.2)	5.2 (5.2)
3	6.1 (7.1)	5.8 (4.9)
9	4.8 (6.0)	6.1 (6.1)
12	5.5 (7.0)	5.1 (5.8)
16	6.2 (8.0)	5.0 (5.8)
23	7.4 (7.6)	3.7 (5.5)
Average	**5.7 (7.1)**	**5.3 (5.5)**

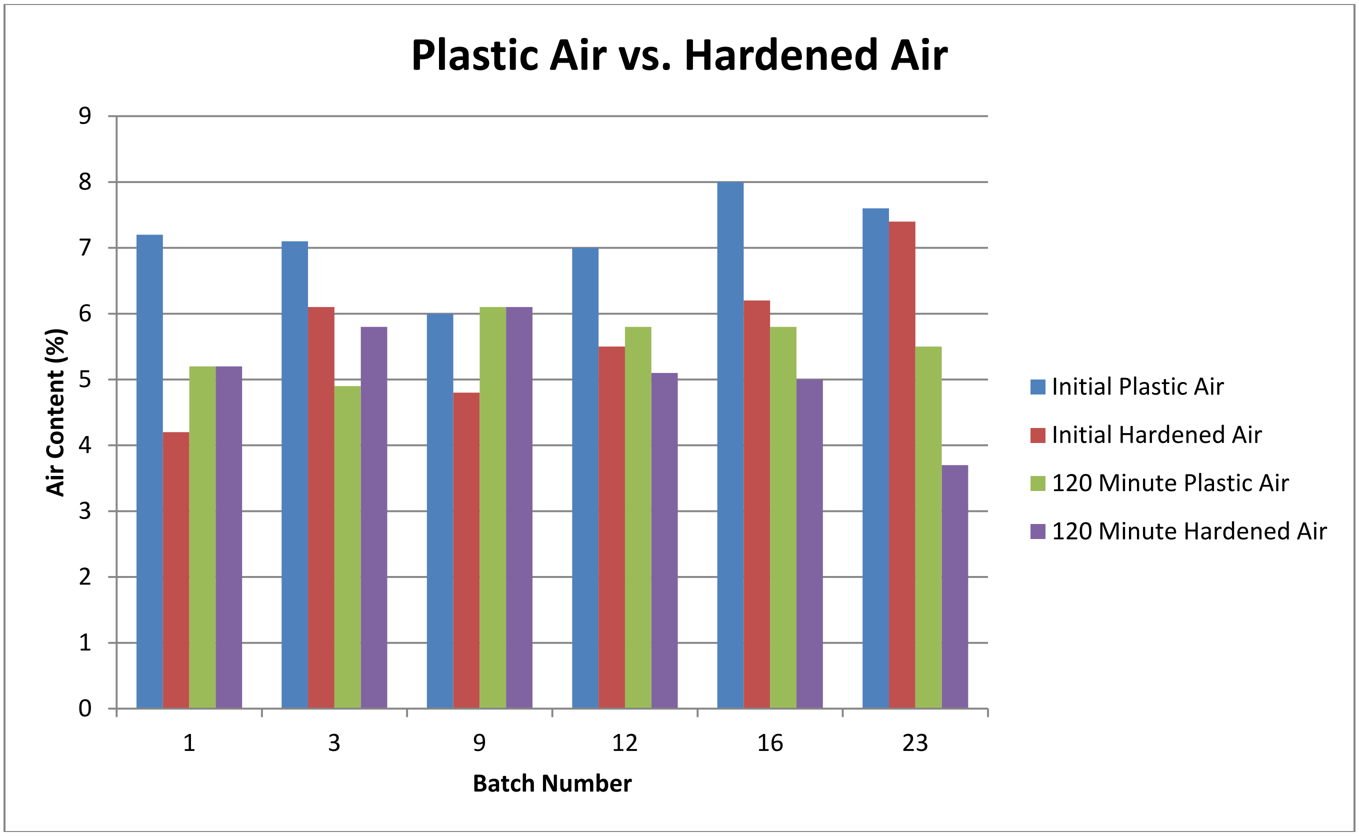


Figure 4. Plastic Air vs. Hardened Air

Table 6 and Figure 5 show the results of the compressive strength tests. It can be seen that there is approximately 300 psi drop in compressive strength at each age between the initial and final samples.

Table 6. Compressive Strength (psi)

Batch No. 1	1-Day	7-Day	28-Day
1I	2230	4480	5760
1F	1740	4300	5980
2I	1800	3980	5930
2F	1670	4320	6110
3I	2230	4130	5670
3F	2000	4230	6140
4I	2100	4810	6780
4F	1820	4390	6130
5I	1630	4020	5620
5F	1560	4200	6120
6I	1140	4070	6190
6F	1120	4230	6010
7I	1370	4150	5860
7F	1280	4430	6050
8I	1240	4580	6540
8F	1250	3820	6820

Batch No. 1	**1-Day**	**7-Day**	**28-Day**
9I	2240	5190	6220
9F	1670	3630	4660
10I	2530	4940	6700
10F	1580	3540	4780
11I	2510	4880	5920
11F	1840	3770	5010
12I	2350	4670	5980
12F	1840	4040	5410
13I	2110	3910	5420
13F	1630	3300	4750
14I	2230	4050	5740
14F	2100	4100	5980
15I	2010	3760	4780
15F	2020	3700	5370
16I	2290	4060	5850
16F	2310	4140	5700
17I	2390	4740	5450
17F	2300	3630	4910
18I	2140	3660	4390
18F	2020	3890	4780
19I	2250	4090	4750
19F	2320	4700	5590
20I	2200	3310	4690
20F	1740	3340	4110
21I	2540	5560	6590
21F	2520	4730	5460
22I	1990	3970	5410
22F	2280	4290	5400
23I	2290	4280	6070
23F	1850	4040	5340
Average Initial	**2060**	**4280**	**5730**
Average Final	**1790**	**3960**	**5380**

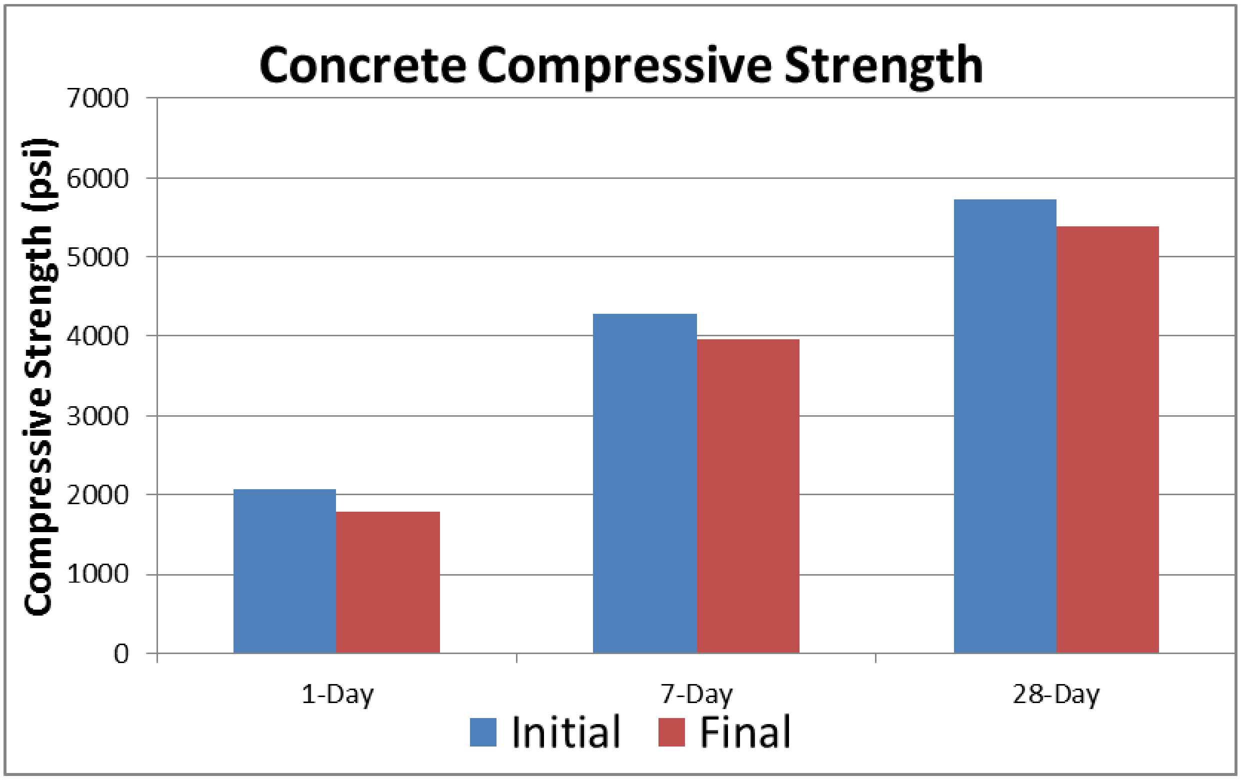


Figure 5. Concrete Compressive Strength

2.5 Freeze-Thaw Test Results

Samples were cast after initial and final mixing and were tested for freeze-thaw durability using ASTM C666 Method A. The results are shown in Table A3 and A4 in Appendix A. The samples cast after the initial mixing had Relative Dynamic Modulus (RDM) values of 88 to 92% after 300 cycles. The samples cast after 120 minutes had RDM values of 87 to 90%. All of the concrete test results indicate that the concrete is durable in freeze-thaw.

CHAPTER 3. CONTROLLED PLANT MIXING PROGRAM

Task 2

3.1 Background

Task 2 of the project consisted of conducting a controlled plant mixing program at a single ready-mix concrete plant on July 29, 2010. MnDOT considered which mixes generally sit in the truck the longest due to placement operations and determined to focus the study on the 3A32 and 3Y43 mixes. In accordance with MnDOT Standard Specifications for construction these specific mixes have the following requirements (Table 7):

Table 7. Mix Design Specifications

Mix Design	Minimum Cementitious Content (pounds per cubic yard)	Anticipated Compressive Strength at 28 days (psi)	Maximum Allowed Slump with a Water Reducer (in)
3A32	560	3900	4
3Y43	640	4300	5

The purpose of Task 2 was to evaluate the two concrete mixes (3A32 and 3Y43) that would be used in Task 3 and determine if there were any modifications to the mixes and/or admixtures that should be made to Task 3.

Task 2 evaluated two configurations of each mix (totaling 4 mixes), 3A32 (which is used primarily for sidewalk and curb and gutter) and 3Y43 (which is used primarily in structures). Air temperature during the sampling and testing was 78^{O}F. Each of the concrete mixes had partial replacement with either fly ash or ground granulated blast furnace slag. The materials used are shown below in Table 8 and Figure 6. Each had a combination of chemical admixtures.

Table 8. Cementitious Materials and Admixtures

Batch No.	Cement	Fly Ash	Slag	Air Entrainment	Mid-Range Water Reducer	Retarder Water Reducer
1	3	1	-	Synthetic #2	-	#6
2	3	-	1	Synthetic #2	-	#6
3	3	1	-	Synthetic #2	-	#6
4	3	-	1	Synthetic #2	-	#6

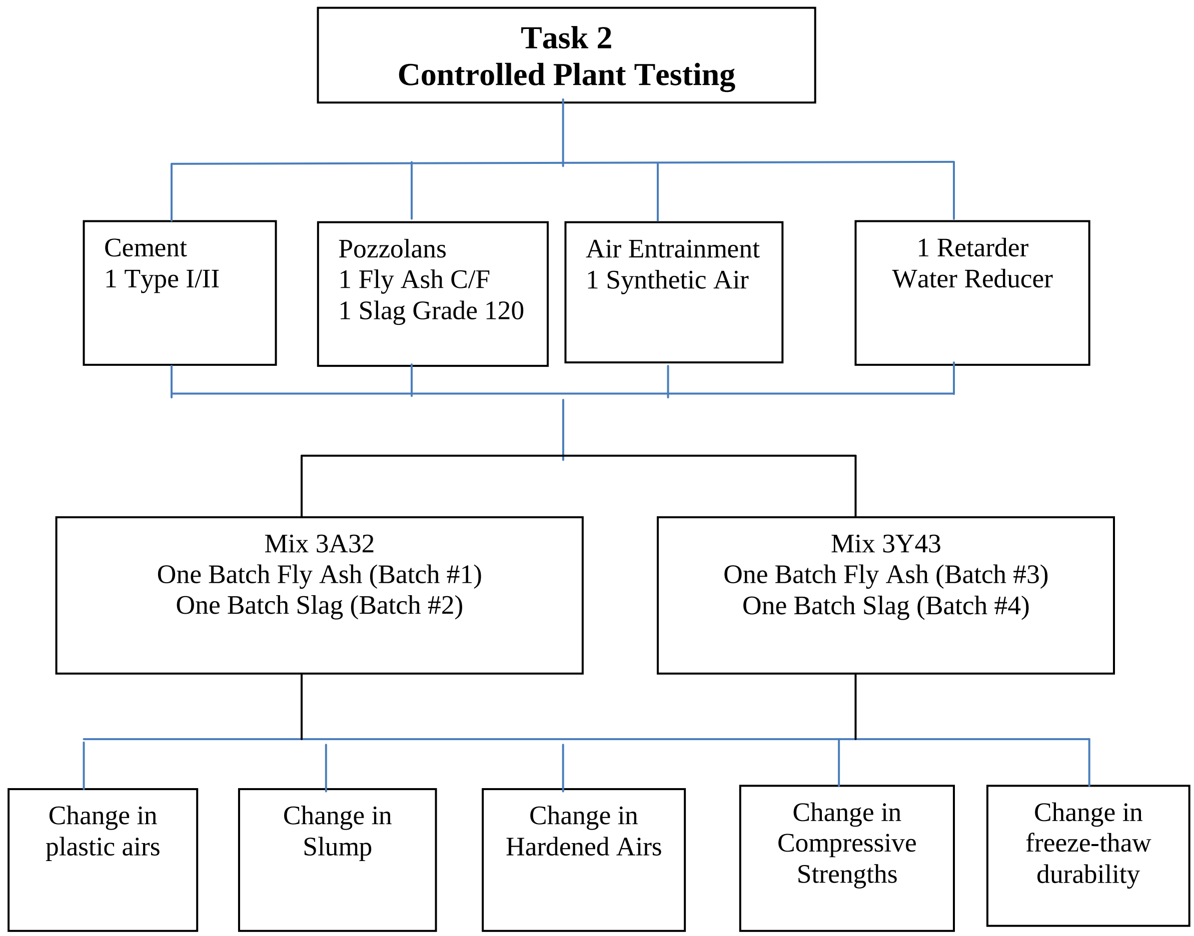


Figure 6. Controlled Plant Testing

Mix Proportions (SSD)

Batch #1- 3A32F

	Mix Design	Adjusted Weights*
Cement, pcy	462	461
Fly Ash, pcy	116 (20%)	116 (20%)
3/4" Gravel, pcy	1,852	1,848
Concrete Sand, pcy	1,229	1,226
Water, pcy	260	259
Water Cementitious Ratio	0.45	0.45

Batch #2- 3A32S

	Mix Design	Adjusted Weights*
Cement, pcy	376	375
Slag, pcy	202 (35%)	201 (35%)
3/4" Gravel, pcy	1,856	1,849
Concrete Sand, pcy	1,231	1,226
Water, pcy	260	259
Water Cementitious Ratio	0.45	0.45

Batch #3- 3Y43F

	Mix Design	Adjusted Weights*
Cement, pcy	524	521
Fly Ash, pcy	131 (20%)	130 (20%)
3/4" Gravel, pcy	1,786	1,776
Concrete Sand, pcy	1,176	1,170
Water, pcy	292	290
Water Cementitious Ratio	0.45	0.45

Batch #4- 3Y43S

	Mix Design	Adjusted Weights*
Cement, pcy	426	415
Slag, pcy	229 (35%)	223 (35%)
3/4" Gravel, pcy	1,794	1,746
Concrete Sand, pcy	1,176	1,145
Water, pcy	292	284
Water Cementitious Ratio	0.45	0.45

*Adjusted weights are based on actual measured weights of each material and unit weight of the plastic concrete.

3.2 Controlled Plant Mixing Program Test Results

The testing program outlined is shown in Figure 6. The mixing method was dry batching, which consisted of mixing the materials in the concrete drum. The concrete was tested for slump, plastic air content, unit weight, and temperature immediately after batching and at 30, 60, 90 and 120 minutes after sampling. Compressive strength data in Table B2 shows compressive strengths at 60, 90, and 120 minutes. Hardened air content and freeze/thaw samples were cast after batching at 60 minutes and at 120 minutes. The ready mix truck drum maintained a 6 revolution spin per minute between sampling for the entire 120 minutes. The individual test results are shown in Appendix B. The testing procedures and methods used are the same as outlined in Task 1.

Table 9 shows that the air content dropped by an average of 0.5% between the initial measurements and at 60 minutes. Between 60 minutes and 120 minutes the air content dropped by an average of 0.3%.

Table 9. Plastic Air Content Measurements (%)

Batch No.	Initial	30 min.	60 min.	90 min.	120 min.
1	7.3	6.7	6.1	5.5	5.5
2	7.1	6.9	7.1	7.0	6.4
3	6.1	5.9	5.6	6.2	6.4
4	8.0	7.6	7.7	7.1	6.8
Average	**7.1**	**6.8**	**6.6**	**6.5**	**6.3**

Table 10 shows the change in slump with time. The slump measurements increased by an average of 2 inches from the initial slump tests after mixing to those taken at 60 minutes. At 90 minutes the slump increased by an average of 2.6 inches. Between 90 and 120 minutes the slump dropped by an average of 1.0 inch.

Table 10. Slump Measurements (inches)

Batch No.	Initial	30 min.	60 min.	90 min.	120 min.
1	7	5.75	4.5	4.5	3
2	7.75	6.75	5.25	4.25	3.25
3	8.5	7.0	6.5	6.0	5.0
4	7.75	7.0	6.5	5.0	4.5
Average	**7.75**	**6.6**	**5.7**	**4.9**	**3.9**

3.3 Hardened Concrete Test Results

After curing for 7 days, samples were tested for hardened air content. It can be seen from Table 11 and Figure 7 that there was a drop in hardened air content (0.6%) between samples taken at 60 minutes and 120 minutes. It can also be seen that there are significant differences in the plastic and hardened air contents of the mixes. The plastic airs are given in (parenthesis) for convenience.

Table 11. Hardened Air (%)

Batch No.	60 min	120 min
1	4.3 (6.1)	3.3 (5.5)
2	6.0 (7.1)	4.6 (6.4)
3	3.7 (5.6)	4.6 (6.4)
4	4.4 (7.7)	4.1 (6.8)
Average	**4.6 (6.6)**	**4.0 (6.3)**

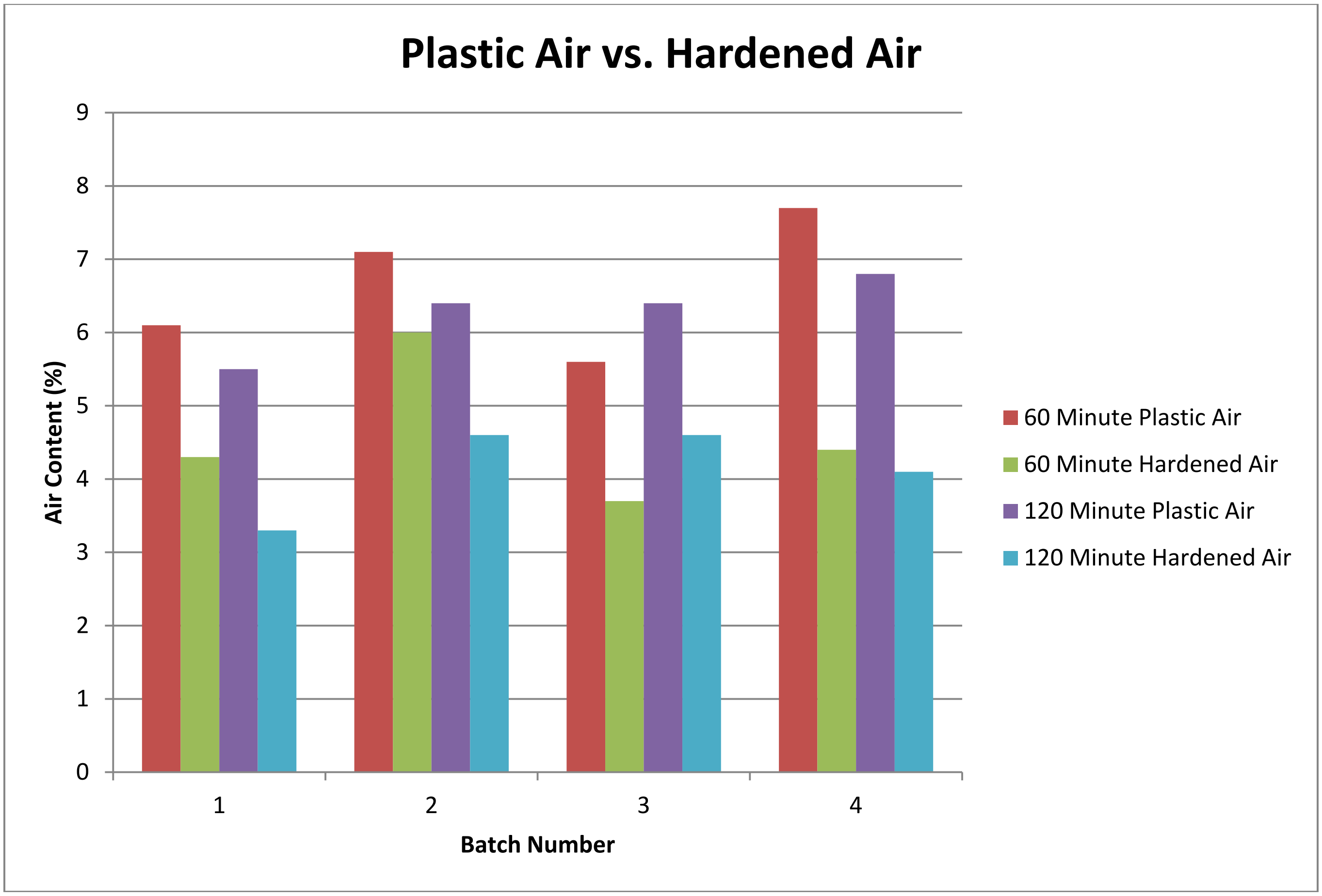


Figure 7. Plastic Air vs. Hardened Air

Table 12 and Figure 8 show results of the compressive strength tests. It can be seen that there is an approximately 160 psi increase in compressive strength between 60 and 120 minutes. The individual results are shown in Table B2.

Table 12. Compressive Strength Results, psi

Batch #	60 minutes*	90 Minutes*	120 Minutes*
1	5430	5820	5940
2	5630	5490	5770
3	5680	4900	5240
4	5790	6120	6200
Average	5630	5580	5790

* Average of 2 cylinders

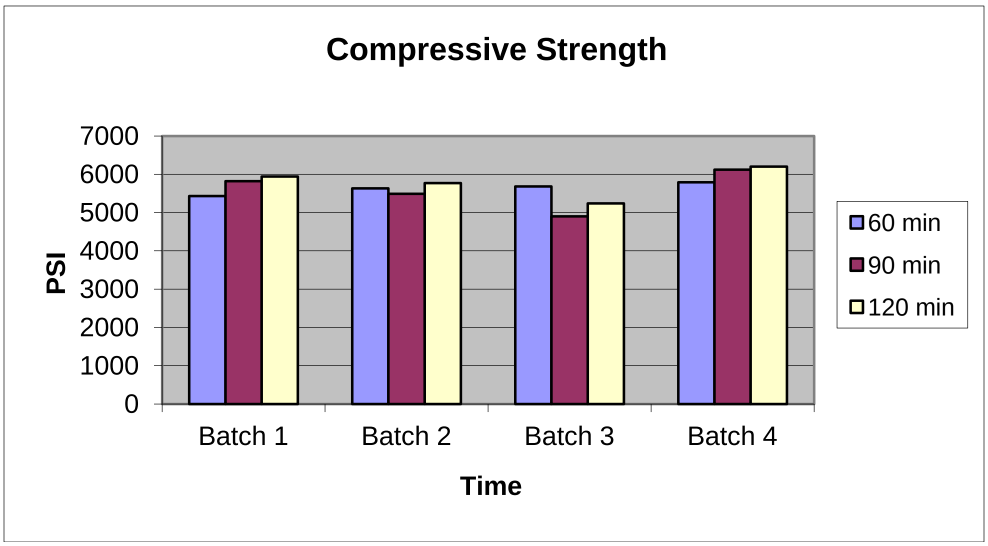


Figure 8. Compressive Strength

3.4 Freeze-Thaw Results

Samples were cast at 60 minutes and 120 minutes after batching. The results are shown in Table B3 in Appendix B. The samples cast 60 minutes after initial mixing had Relative Dynamic Modulus (RDM) values of 82 to 88% after 300 cycles. The samples cast after 120 minutes had RDM values of 82 to 87%. All of the concrete tests results indicate that the concrete is freeze-thaw durable.

CHAPTER 4. REGIONAL TESTING

Task 3

4.1 Background

Following the controlled plant mixing program, the work plan for the regional testing program was finalized. It was determined, after discussions with the participating ready-mix suppliers that all of the concrete mixes would have cementitious materials consisting of cement and fly ash – no slag was used. The ready-mix suppliers were selected based upon willingness to work with the research team and geographic location – plants in each region of the state and 3 plants in the St. Paul/Minneapolis metropolitan area were selected. The plants are shown below in Table 13.

Table 13. Cementitious Materials and Admixtures

Batch No.	Cement	Fly Ash	Air Entrainment	Mid-Range Water Reducer	Retarder Water Reducer
Rochester Ready Mix					
5 (3A32)	1	2	Vinsol Resin #1	-	6
6 (3Y43)	1	2	Vinsol Resin #1	-	6
Duluth Ready Mix					
7 (3A32)	2	1	Synthetic #3	-	2
8 (3Y43)	2	1	Synthetic #3	-	2
G.C.C. St. James					
9 (3A32)	3	1	Vinsol Resin #2	-	1
10 (3Y43)	3	1	Vinsol Resin #2	-	1
Knife River Baxter					
11 (3A32)	1	3	Synthetic #2	1	4
12 (3Y43)	1	3	Synthetic #2	1	4
Cemstone St. Paul					
13 (3A32)	2	1	Vinsol Rosin #2	4	5
14 (3Y43)	2	1	Vinsol Rosin #2	4	5
AVR Burnsville					
15 (3A32)	1	2	Vinsol Rosin #2	4	5
16 (3Y43)	1	2	Vinsol Rosin #2	4	5
Aggregate Industries-					
Mpls.	2	1	Synthetic #1	3	3
17 (3A32)	2	1	Synthetic #1	3	3
18 (3Y43)					

4.2 Regional Testing Program

For the regional testing program, two concrete mixes were tested that were supplied by 7 different ready-mix plants. The mixes consisted of a 3A32 and a 3Y43, each with partial replacement of cement with fly ash, ranging from 15% to 20%, depending upon the supplier. Air temperature during the sampling and testing ranged from $50^{O}F$ to $77^{O}F$. The testing program outlined is as shown in Figure 9. As with Task 2, the concrete was tested for slump, plastic air content, unit weight, and temperature immediately after batching and at 60, 90 and 120 minutes after sampling. Compressive strength, hardened air content, and freeze/thaw samples were cast after batching (60 minutes) and at 120 minutes. The test results from each concrete plant are shown in Appendix C. The testing procedures and methods used are the same as outlined in Task 1.

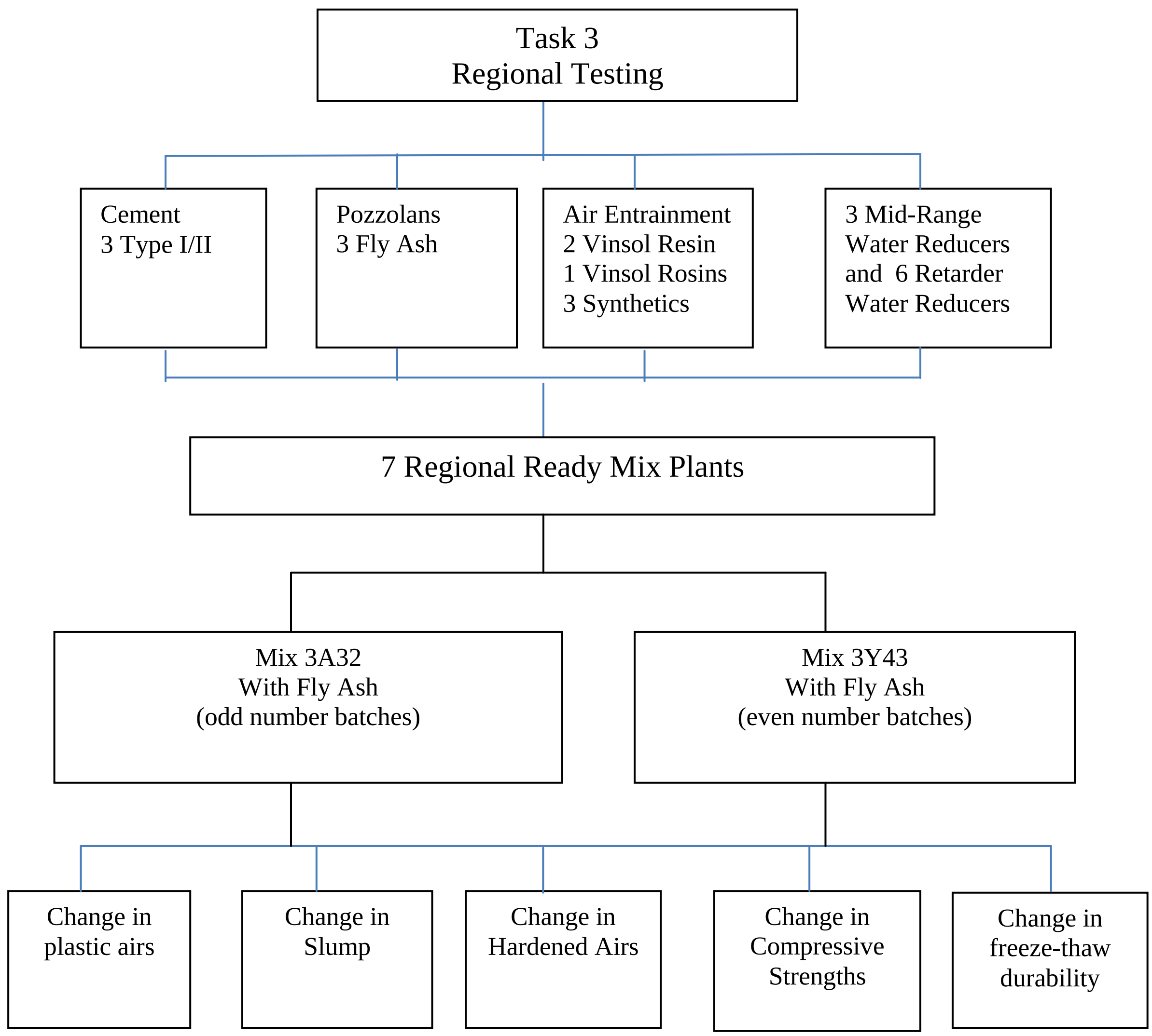


Figure 9. Regional Testing

4.3 Regional Testing Program Test Results

The concrete was tested for slump, plastic air content, unit weight, and temperature immediately after batching and at 60, 90, and 120 minutes after sampling. The ready mix truck drum maintained a 6 revolution spin between sampling for the entire 120 minutes. Compressive strength, hardened air content, and freeze-thaw samples were cast after 60 minutes and at 120 minutes. The individual test results are shown in Appendix C. It can be seen in Table 14 that the air content change between the initial measurement and at 60 minutes dropped by an average of 1.6%. Between 60 minutes and 120 minutes the air content dropped by an average of 1.3%.

Table 14. Plastic Air Content Measurement (%)

Batch No.	Initial	30 min.	60 min.	90 min.	120 min.
5	7.5	7.2	6.8	5.8	5.2
6	8.0	7.8	7.3	6.5	6.0
7	9.0	8.5	8.2	7.9	7.5
8	8.3	7.2	7.5	6.9	6.0
9	10.0	9.2	7.5	6.6	6.2
10	8.2	7.6	6.9	5.9	4.9
11	6.2	4.7	3.8	3.5	3.2
12	6.5	4.9	3.7	2.6	5.2
13	8.2	7.5	5.9	5.7	3.0
14	9.5	8.9	7.2	6.8	5.5
15	4.6	4.6	3.8	3.2	3.2
16	5.7	4.5	4.3	3.8	3.6
17	9.9	8.4	8.0	7.3	6.7
18	9.0	8.5	6.7	5.0	4.0
Average	**7.9**	**7.1**	**6.3**	**5.5**	**5.0**

Table 15 shows the change in slump with time from the initial slump tests after mixing to those taken at 60 minutes. The slump measurements decreased by an average of 1.5 inches between initial and 60 minutes. The slump decreased by an average of 2.3 inches between initial and 90 minutes. Between 90 and 120 minutes the slump dropped by an average of 0.9 inches.

Table 15. Slump Measurements (inches)

Batch No.	Initial	30 min.	60 min.	90 min.	120 min.
5	7.5	6.75	5.0	4.75	3.25
6	8.75	8.0	7.5	7.0	6.0
7	8.0	7.5	6.75	6.0	5.0
8	7.0	6.75	6.25	5.5	4.75
9	7.0	6.75	7.25	5.25	4.75
10	9.0	8.5	8.75	8.25	7.5
11	3.75	3.0	1.75	1.0	0.75
12	9.0	9.0	9.0	9.0	8.75
13	5.5	4.75	4.0	3.0	1.5
14	6.0	5.75	4.75	3.0	1.25
15	4.25	3.5	1.25	1.0	0.5
16	6.5	5.25	3.5	2.0	1.25
17	5.5	9.0	4.5	4.0	3.25
18	6.0	4.0	2.5	1.5	1.0
Average	**6.7**	**6.3**	**5.2**	**4.4**	**3.5**

4.4 Hardened Concrete Test Results

After curing for 7 days, samples were tested for hardened air content. It can be seen from Table 16 and Figure 10 that there was a drop in hardened air content (1.3%) between samples taken at 60 and 120 minutes. It can also be seen that there are significant differences in plastic and hardened air contents of the mixes. The plastic airs are given in (parenthesis) for convenience.

Table 16. Hardened Air (%)

Batch No.	60 min.	120 min.
5	4.5 (6.8)	3.7 (5.2)
6	6.8 (7.5)	4.6 (6.0)
7	8.4 (8.2)	6.4 (7.5)
8	8.3 (7.5)	6.7 (6.0)
9	6.8 (7.5)	5.5 (6.2)
10	3.8 (6.9)	3.6 (4.9)
11	3.0 (3.8)	2.5 (3.2)
12	5.4 (3.7)	2.4 (5.2)
13	5.8 (5.9)	2.8 (3.0)
14	5.2 (7.2)	5.0 (5.5)
15	4.2 (3.8)	4.4 (3.2)
16	3.0 (4.3)	3.1 (3.6)
17	6.2 (8.0)	4.6 (6.7)
18	5.2 (6.7)	3.9 (4.0)
Average	**5.5 (6.3)**	**4.2 (5.0)**

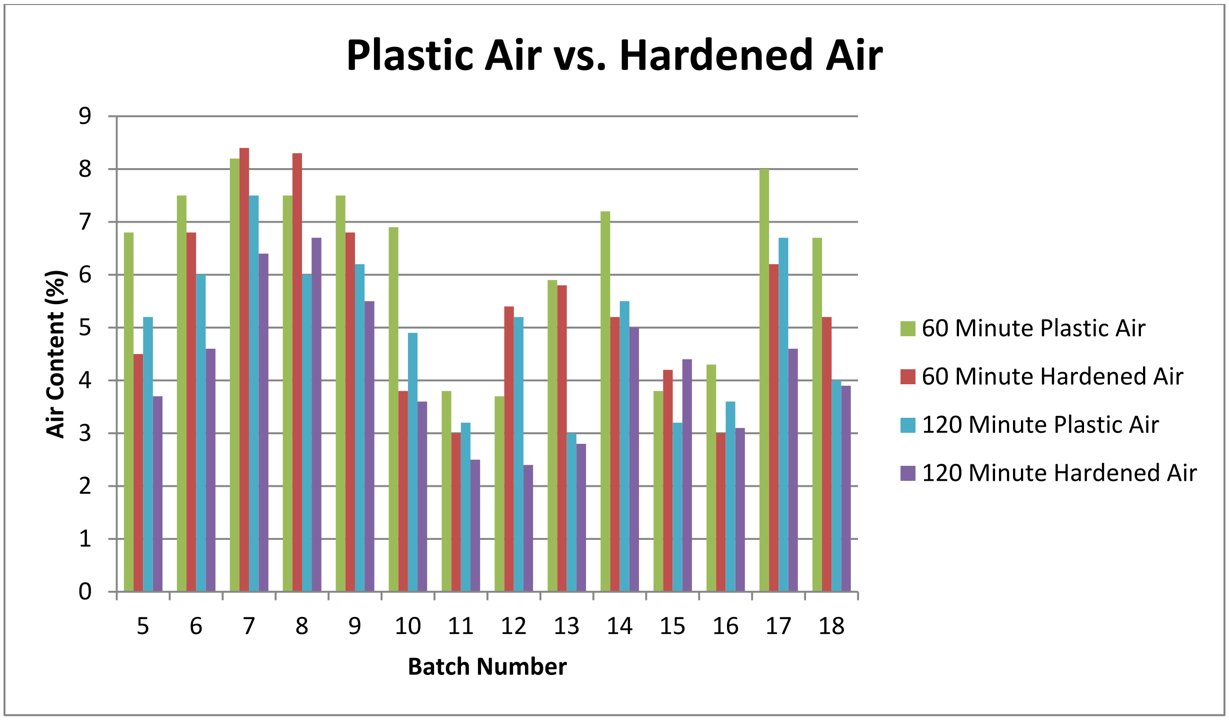


Figure 10. Plastic Air vs. Hardened Air

Table 17 shows results of the compressive strength tests. It can be seen that there is an approximately 280 psi increase in compressive strength between 60 and 120 minutes.

Table 17. Compressive Strength Results (psi)

Batch No.	60 min.*	90 min.*	120 min.*
5	5570	5420	5450
6	5070	5080	4830
7	3220	3670	3970
8	4510	4710	5230
9	4730	5060	5450
10	4610	4910	5380
11	7810	6970	7240
12	6630	6450	6370
13	4380	5030	5500
14	4450	4310	4780
15	7720	7320	7300
16	8080	7400	7710
17	5320	5380	5410
18	6140	6630	7620
Average	**5590**	**5600**	**5870**

*Average of 2 cylinders

4.5 Freeze-Thaw Test Results

Samples were cast at 60 minutes and 120 minutes after batching. The results are shown in Tables C5, C11, C16, C21, C26, C31, and C36 in Appendix C. The samples cast at 60 minutes after initial mixing had Relative Dynamic Modulus (RDM) values of 83 to 93% after 300 cycles. The samples cast after 120 minutes had RDM values of 86 to 94%. All of the concrete test results indicate that the concrete is freeze-thaw durable.

CHAPTER 5. STATISTICAL ANALYSIS

Two approaches for statistical analysis were accomplished. The first approach was performed by Ally Akkari of MnDOT and compared the results of air, slump, compressive strength and freeze-thaw durability tests for each concrete mixture at two points in time using a two-tailed paired T-test. This analysis was done separately for each data set (i.e., Task 1, Task 2 and Task 3) to determine whether the average differences in each test result at the two times were statistically significant. This approach ignores the impact of other mix design variables on the test results; these differences are negligible for the Task 3 data, minor for the Task 2 data, but significant for the Task 1 data, so the analytical results must be considered in the appropriate context for each of these tasks. In addition to the T-Test analysis, a Wilcoxon signed rank test was performed.

The second approach was performed by Dr. Mark Snyder and looked at the effect that each of the mix design variations (e.g., changes in cement content, changes in admixture type, etc.) had on the air, slump, compressive strength, and durability at each of the points in time.

5.1 Statistical Analysis Approach #1

5.1.1 Paired students T-Test, 95% Confidence

The following tests compare slump, air, compressive strength, and durability for a single mix at different delivery times. In this analysis, the null hypothesis is that the property is equal at both delivery times, and the alternative hypothesis is that it is different. Therefore, to reject the null hypothesis and be considered significant, the P(null) must be less than 0.1 for 90% confidence, and less than 0.05 for 95% confidence. Significant differences found from this analysis are shaded in Tables 18 through 22.

<u>Summary – Change in Delivery time from 60 to 90 minutes and from 60 to 120 minutes</u>

Table 18. Change in Air (%)

	60 to 90 minutes			60 to 120 minutes		
	Task 1*	Task 2**	Task 3	Task 1*	Task 2**	Task 3
P stat Paired T-Test	**0.008**	0.5813	**0.000014**	0.201	0.4339	**0.000774**
Average Change	0.79	-0.18	-0.72	0.36	-0.35	-1.24
95% Upper Limit	1.35	1.08	-0.48	0.91	-0.73	-0.63
95% Lower Limit	0.23	0.89	-1.16	-0.20	-1.59	-1.86
P<0.05 is significant. Delivery time affects property						
*Task 1 includes remixing at 90 minutes, causing increase in slump/air **Task 2 Only has 4 pairs to compare						

Table 19. Change in Slump (in)

	60 to 90 minutes			60 to 120 minutes		
	Task 1*	Task 2**	Task 3	Task 1*	Task 2**	Task 3
P stat Paired T-Test	**0.000944**	0.0663	**0.000153**	0.132	**0.0012**	**0.000004**
Average Change	0.88	-1.00	-0.82	0.34	-1.75	-1.66
95% Upper Limit	1.36	0.13	-0.48	0.78	-1.29	-1.18
95% Lower Limit	0.40	-2.13	-1.16	-0.11	-2.21	-2.14

Table 20. Compressive Strength – Task 1

	1 Day	7 Day	28 Day
P (0 min = 120 min)	0.0009	0.0353	0.1093
P(0 min ≠ 120 min)	0.9991	0.9647	0.8907
Significance	Delivery time will change strength at over a 99% confidence level	Delivery time will change strength to a 95% confidence level	Delivery time does not significantly change strength (even at 90% confidence level)
Average Difference	**-232.6**	**-283.9**	**-247.826**

Table 21. Compressive Strength – Task 3

	60 min to 90 min	60 min to 120 min
P(t1=t2)	0.952	0.121
P(t1≠t2)	0.048	0.879
Significance	Change in delivery time does not significantly change strength	Change in delivery time does not significantly change strength
Average Difference	**7.14**	**285.71**

<u>Durability Factor</u>

Table 22. Change in Delivery Time

Task	**Change in Delivery Time**	**P(t1=t2)**	**P(t1≠t2)**
Task 1	0 to 120 min	0.00017	0.99983
*Task 2	60 to 120 min	0.22921	0.77080
Task 3	60 to 120 min	0.56275	0.43725

*Task 2 only 3 pairs

Observation: As shown in Table 22, there is only a significant change in DF from 0 to 120 minutes in task 1. In tasks 2 and 3, there is not a significant change in DF for a change in delivery time.

Wilcoxon Signed Rank Test

Description

The Wilcoxon Signed Rank Test is a non-parametric alternative to the Student's Paired T-Test. Although results are sometimes considered less powerful than those from the Student's Paired T-Test, it requires much less strict restrictions on the sample population. It does not assume the sample population to be normally distributed. This procedure uses the differences of between matched pairs of two sample populations to test the null hypothesis that the median difference is equal to zero. The only assumption made is that the sample differences are symmetric about a shared median value. The absolute values of the differences are ranked in ascending order. Tied differences are assigned an averaged rank. Pairs with zero differences are excluded from the analysis. The signs of the paired differences are applied to each rank. Finally, the test statistic S is calculated by summing the signed ranks. For sample sizes smaller than 20, the exact statistical probability of obtaining a particular S value can be calculated by determining all the different possible distributions of the ranks. For sample sizes larger than 20, the exact probability becomes tedious to compute. However, the distribution of possible ranks becomes more normally distributed as sample size increases, and the normal approximation of the probability can be used.

As with the Student's T-Test, slump, air, freeze thaw, and compressive strength were compared at 60 to 90 minutes, and at 60 to 120 minutes, using measurements from a single mix as a pair. Results at difference delivery times were considered to be significantly different if the resulting two-tailed probability from the Wilcoxon Signed Rank Test was less than 0.05 (the 95% confidence level).

Results

Unlike the T-Test, the Wilcoxon does not give a probable range for the mean difference between the two delivery times. However, the P statistic may be more appropriate for the data in this research as it is not based off the assumption of a particular sample distribution and the many different mixes used in this study make the sample sets highly variable. As was done with the Paired Student's T-Test, a significance level of 0.05 is used to determine if the results of a particular property are statistically different at different delivery times. These cases are highlighted and bold in the tables below.

Table 23 shows the results from the Wilcoxon Signed Rank Test of all air and slump changes from 60 minutes to 90 and 120 minutes. The test found a significant difference in slump and air in both the lab and field study at 90 minutes and in the field study at 120 minutes. Again, the small sample sizes in plant study make the results of the test statistically insignificant.

Table 23. Wilcoxon Signed Rank Test – Slump and Air

Property	**Air**					
Change	60 to 90 minutes			60 to 120 minutes		
Study	Lab	Plant	Field	Lab	Plant	Field
Sum of Negative Ranks	-208	-3	0	-117	-3	-8.5
Sum of Positive Ranks	45	7	105	93	7	96.5
Exact P Value		0.3125	0.0001	0.6424	0.3125	0.0015
P Value for Normal Approximation	0.0085	0.5839	0.0011	0.6677	0.5839	0.0063
Total Ties	16	3	6	14	3	9
Number of Zero Differences Dropped	1	0	0	3	0	0
Cases	22	4	14	20	4	14
Property	**Slump**					
Change	60 to 90 minutes			60 to 120 minutes		
Study	Lab	Plant	Field	Lab	Plant	Field
Sum of Negative Ranks	-174	0	0	-178	0	0
Sum of Positive Ranks	16	6	91	75	10	105
Exact P Value	0.0003	0.1250	0.0001		0.0625	0.0001
P Value for Normal Approximation	0.0016	0.1814	0.0017	0.0978	0.1003	0.0011
Total Ties	14	2	10	21	4	9
Number of Zero Differences Dropped	4	1	1	1	0	0
Cases	19	3	13	22	4	14

Table 24 provides the Wilcoxon Test results for durability factor and hardened air content. The test shows that durability factors are only significantly different between 0 to 60 minutes in the lab study, and that hardened air content is only significantly different between 60 and 120 minutes in the field study.

Table 24. Wilcoxon Signed Rank Test – Durability and Hardened Air

Property	**Durability Factor**			**Hardened Air**		
Change	0 to 60 min	60 to 120 min	60 to 120 min	0 to 60 min	60 to 120 min	60 to 120 min
Study	Lab	Plant	Field	Lab	Plant	Field
Sum of Negative Ranks	-11	-1	-36	-8	-2	-4
Sum of Positive Ranks	160	5	55	13	8	101
Exact P Value	0.0002	0.2500	0.3116	0.3437	0.1875	0.0004
P Value for Normal Approximation	0.0013	0.4220	0.5294	0.6750	0.3613	0.0026
Total Ties	18	0	12	0	0	9
Zero Differences Dropped	5	0	1	0	0	0
Cases	18	3	13	6	4	14

Finally, Table 25 gives the test results from compressive strength measurements. This property showed the least significant change due to a change in delivery time, with the only one day strength measurements from the lab study being statistically different at 0 and 120 minutes.

Table 25. Wilcoxon Signed Rank Test – Compressive Strength

Change	0 to 120 min	0 to 120 min	0 to 120 min	60 to 90 min	60 to 120 min
Study	Lab	Lab	Lab	Plant	Field
Age (days)	1	7	28	28	28
Sum of Negative Ranks	-28.5	-86	-93	-57	-75
Sum of Positive Ranks	247.5	190	182.5	48	30
Exact P Value				0.5131	0.0931
P Value for Normal Approximation	**0.0009**	0.1173	0.1808	0.8017	0.1673
Total Ties	11	6	2	0	2
Zero Differences Dropped	0	0	0	0	0
Cases	23	23	23	14	14

5.2 Statistical Analysis Approach #2

The data from each of the individual Tasks of the project were evaluated statistically to determine if any of the variables in the mixes appeared to have any significant effect on the performance of the concrete. The mixes from each Task were evaluated individually, so that the mixing was not included as an additional variable. Due to budgetary constraints, replicates were not included in the research.

5.2.1 Task 1

The twenty-three runs that comprise the initial laboratory study represent five test variables with up to seven levels:

- Cement type (three types)
- Fly ash type (three types)
- Air-entraining admixture type (five types)
- Mid-range water-reducer (four types plus “none”)
- Retarding water-reducer type (seven types).

A complete factorial experimental design that would determine the effects of all of these variables and their interactions would require 3 x 3 x 5 x 5 x 7 = 1575 tests. A fractional factorial experimental design could have been performed to give reasonable estimates of the primary and two-way interaction effects, but it appears that this was not possible. In addition, the lack of replicate runs (preparation and testing of separate but identical batches) was also impossible due to funding and time limitations, so it is also difficult to assess the variability and significance of some of the test results (i.e., to determine which are statistically significant).

Some subsets of the data can be considered to evaluate the effects of specific variables over certain ranges. The following subsets were identified as being the most useful:

- Batches 1 – 8: Evaluate effects of fly ash types 1 and 2 and air-entrainment types 1 and 2 with two combinations of cement type and RWR [cement 2 and RWR 2 vs. cement 1 and RWR 3] (note: this is an expanded version of the first two subsets that provides additional insight into variable interactions)
- Batches 5 – 12, 15, 16, 18, 19: Evaluate effects of fly ash types 1 and 2 for various combinations of chemical admixtures, all over cement type 1.
- Batches 13 – 16: Evaluate effects of fly ash types 1 and 2 and cement types 1 and 3 over a constant chemical admixture combination (air entrainer 4, MRWR 2 and RWR 6).
- Batches 17, 18, 20, 21: Evaluate effects of fly ash types 1 and 3 over two combinations of cement type and chemical admixtures (cement 1, AE 5, MRWR3 and RWR 7 vs. cement 1, AE3, no MRWR and RWR 5).

The primary outputs of interest (dependent variables) are assumed to be 28-day compressive strength, durability factor, dilation and mass loss. The effects of each independent variable in the data subsets above on each of these dependent variables is described in the sections below.

<u>Batches 1–8: Effects of fly ash types 1 and 2 and air-entrainment types 1 and 2 with two combinations of cement type and RWR (cement 2 and RWR 2 vs. cement 1 and RWR 3)</u>

Table 26 presents a summary of the gross averages, ranges and standard deviations of the primary test results of interest for Task 1. It can be seen that the average compressive strength of all mixtures and transit times tested is well above typical design strengths and that 28-day compressive strength, on average, increased with the change in transit time from 0 to 120 minutes (although the increase is not statistically significant). Similarly, it can be seen that average durability factor test results are all well above typically accepted minimums of 80 for highly durable concrete. Increasing transit time from 0 to 120 minutes reduced durability factors by an average of 1.4, although the decrease is not statistically significant. Finally, dilation values are similarly good for all test values (above a typical threshold of 0.1% or 0.04%/100 cycles) and that there is no significant change in dilation with the increased transit time.

Table 26. Summary of Gross Averages for Batches 1-8

	Average	Range	Std. Dev.
f'c (28-day), psi			
t = 0	6044	5670 - 6780	424
t = 120	6170	5980 - 6820	269
Δ (t =0 to t = 120)	126	-650 - 500	377
DF			
t = 0	90.125	88 - 92	1.8
t = 120	88.75	87 - 90	1.2
Δ (t =0 to t = 120)	-1.4	-3 – 0	1.1
Dilation, %			
t = 0	0.03	0.03	0
t = 120	0.029	0.02 – 0.03	0.004
Δ (t =0 to t = 120)	-0.00013	-0.01 - 0	0.004

In summary, analysis of the data from this subset of Task 1 tests indicates that all of the mixtures produced were of sufficient strength and durability for highway construction, and there was generally little significant impact of any of the test variables on concrete durability. The use of fly ash 2 appeared to produce somewhat higher 28-day compressive strengths than fly ash 1, but even this difference cannot be considered highly significant given the small amount of available test data.

<u>Batches 5–12, 15, 16, 18, and 19: Effects of fly ash types 1 and 2 for various combinations of chemical admixtures, all over cement type 1</u>

Table 27 presents a summary of the gross averages, ranges and standard deviations of the primary test results of interest for Task 1. It can be seen that the average compressive strength of all mixtures and transit times tested is well above typical design strengths and that 28-day compressive strength, on average, increased with the change in transit time from 0 to 120 minutes (although the increase is not statistically significant).

Similarly, it can be seen that average durability factor test results are all well above typically accepted minimums of 80 for highly durable concrete. Increasing transit time from 0 to 120 minutes reduced durability factors by an average of 1.0, although the decrease is not statistically significant. Finally, dilation values are good for all test values (above the typical threshold of 0.1% or 0.04%/100 cycles) and that there is no significant change in dilation with the increased transit time.

Table 27. Summary of Gross Averages for Batches #5-12, 15, 16, 18, and 19

	Average	Range	Std. Dev.
f'c (28-day), psi			
t = 0	5733	4390 – 6700	729
t = 120	5525	4660 – 6820	656
Δ (t =0 to t = 120)	-208	-840 – 1920	873
DF			
t = 0	90	88 – 92	1.2
t = 120	89	88 – 90	0.7
Δ (t =0 to t = 120)	-1.0	-2.0 – 1.0	1.0
Dilation, %			
t = 0	0.030	0.030	0
t = 120	0.030	0.030	0
Δ (t =0 to t = 120)	0	0	0

In summary, analysis of the data from this subset of the Task 1 tests indicates that all of the mixtures produced were of sufficient strength and durability for highway construction, and there was generally little significant impact of any of the test variables on concrete durability. The use of fly ash 2 appeared to produce somewhat higher 28-day compressive strengths than fly ash 1, but even this difference cannot be considered highly significant given the small amount of available test data.

The use of various combinations of chemical admixtures sometimes had significant effects on concrete strength. Many of these combinations resulted in significantly lower strength at longer transit times. Admixture combination 2 generally seemed to produce the best results for long transit times and admixture combination 1 produced similar (but slightly lower) strengths.

<u>Batches 13–16: Effects of fly ash types 1 and 2 and cement types 1 and 3 over a constant chemical admixture combination (air entrainer 4, MRWR 2 and RWR 6)</u>

Table 28 presents a summary of the gross averages, ranges and standard deviations of the primary test results of interest for Task 1. It can be seen that the average compressive strength of all mixtures and transit times tested is well above typical design strengths and that there was no apparent (or statistically significant) difference in 28-day compressive strength with increased transit time from 0 to 120 minutes.

It can also be seen in Table 5 that average durability factor test results are all well above typically accepted minimums of 80 for highly durable concrete. Increasing transit time from 0 to 120 minutes reduced durability factors by an average of 1.8, although the decrease is not statistically significant. Finally, dilation values are similarly good for all test values (above a typical threshold of 0.1% or 0.04%/100 cycles) and that there is no apparent or significant change in dilation with the increased transit time for this data subset.

Table 28. Summary of Gross Averages for Batches 13-16

	Average	Range	Std. Dev.
f'c (28-day), psi			
t = 0	5448	4780 – 5850	481
t = 120	5450	4750 – 5980	529
Δ (t =0 to t = 120)	3	-590 – 670	541
DF			
t = 0	90	89 – 91	0.8
t = 120	88	87 – 89	1.0
Δ (t =0 to t = 120)	-1.8	1 – 3	1.0
Dilation, %			
t = 0	0.03	0.03	0
t = 120	0.03	0.03	0
Δ (t =0 to t = 120)	0	0	0

In summary, analysis of the data from this subset of Task 1 tests indicates that all of the mixtures produced were of sufficient strength and durability for highway construction, and there was generally little significant impact of any of the test variables on concrete durability. The use of fly ash 2 appeared to produce somewhat higher 28-day compressive strengths than fly ash 1, but even this difference cannot be considered highly significant given the small amount of available test data. The use of cement 3 rather than cement 1 had no significant impact on concrete strength.

<u>Batches 17, 18, 20, and 21: Evaluate effects of fly ash types 1 and 3 over two combinations of chemical admixtures (AE 5, MRWR3 and RWR 7 vs. AE3, no MRWR and RWR 5)</u>

Table 29 presents a summary of the gross averages, ranges and standard deviations of the primary test results of interest for Task 1. It can be seen that the average compressive strength of all mixtures and transit times tested is well above typical design strengths, although there was a trend toward reduced compressive strengths with increased transit time (average reduction of 465 psi).

It can also be seen in Table 29 that average durability factor test results are all well above typically accepted minimums of 80 for highly durable concrete. Increasing transit time from 0 to 120 minutes had no apparent or significant reduction effect on either durability factor or dilation (which was very good for all test results within this data subset).

Table 29. Summary of Gross Averages for Batches #17, 18, 20 and 21

	Average	Range	Std. Dev.
f'c (28-day), psi			
t = 0	5280	4390 – 6590	981
t = 120	4815	4110 – 5460	555
Δ (t =0 to t = 120)	-465	-1130 – 390	630
DF			
t = 0	89.5	89 – 91	1.0
t = 120	89.3	89 – 90	-.5
Δ (t =0 to t = 120)	-0.3	-1.0 – 0.0	0.5
Dilation, %			
t = 0	0.03	0.03	0.03
t = 120	0.03	0.03	0.03
Δ (t =0 to t = 120)	0	0	0

In summary, analysis of the data from this subset of Task 1 tests indicates that all of the mixtures produced were of sufficient strength and durability for highway construction, and there was little apparent or significant impact of either of the test variables on concrete durability. The use of fly ash 3 appeared to produce higher 28-day compressive strengths than fly ash 1 (particularly for zero transit time batches). The use of admixture combination 7 (rather than 6) also appeared to result in higher strengths for short transit time, but this difference cannot be considered highly significant given the small amount of available test data.

Summary of Conclusions from Task 1 Test Results

The following overall conclusions can be drawn from this analysis of the results of the laboratory testing performed under Task 1:

- All batches produced under this task had excellent resistance to freezing and thawing, as indicated by their high durability factors and relatively low dilation values. None of the treatments used in Task 1 (i.e., different cements, fly ash types, or admixture combinations) had any significant impact on concrete freeze-thaw durability.
- The effect of changing cement type from 1 to 2 is confounded with a coincident change of retarding water-reducers from 3 to 2. The two effects cannot be separated using the data from this study. However, the combined effect of the two on concrete strength was insignificant.
- Changing cement type from 1 to 3 had no significant effect on concrete strength for either transit time.
- The effect of changing fly ash type from 1 to 2 generally resulted in increased 28-day compressive strengths for both transit times, especially when transit time was low (t=0).
- Changing fly ash type from 1 to 3 resulted in greatly increased strength for both transit times. Given the lack of replicate data, it is impossible to say that the increase at t = 120 mins is statistically significant, but the increase for t = 0 (1480 psi) is highly significant.

- The use of various combinations of chemical admixtures sometimes had significant effects on concrete strength. Many of these combinations resulted in significantly lower strength at longer transit times. Admixture combination 2 generally seemed to produce the best results for long transit times and admixture combination 1 produced similar (but slightly lower) strengths.
- Most two- and three-way interactions observed were negligible and almost certainly were not statistically significant (although additional data runs would be required to determine significance).

5.2.2 Task 2

The four runs that comprise the controlled field mix study represent a complete factorial experimental design of two test variables with two levels each:

- Total cementitious content (578 pcy vs. 655 pcy)
- SCM type and replacement level (20% fly ash vs. 35% slag cement)

All other mix design factors (e.g., w/(c+p), aggregate sources, cement source/type, etc.) were held approximately constant.

The primary outputs of interest (dependent variables) are assumed to be slump, plastic air content, hardened air content, 28-day compressive strength, durability factor, dilation and mass loss. The effects of total cementitious content and SCM type/replacement level on each of these test results are described below.

It should be noted that there were no true replicate runs in this task (i.e., preparation and testing of separate but identical batches) due to funding and time limitations, so it is difficult to assess the variability and significance of the test results (i.e., to determine which are statistically significant). However, some trends in the data are apparent, as described below.

Table 30 summarizes the gross averages of the test results for the Task 2 batches. Some observations that can be drawn from this table include:

- The loss of slump that resulted from increasing transit time from 60 minutes to 120 minutes ranged from 1.5 to 2 inches and averaged 1.75 inches. Actual slump values at 120 minutes averaged nearly 4 inches, which is adequate for many concrete construction applications.
- The loss of plastic air that resulted from increasing transit time from 60 to 120 minutes averaged 0.35 percent. In one case (655 lbs c+p, 20 percent fly ash), the added transit time resulted in increased air. Plastic air content after 120 minutes ranged from 5.5 to 6.8 percent.
- The loss of hardened air that resulted from increasing transit time averaged 0.45 percent. In one case (655 lbs c+p, 20 percent fly ash), the added transit time resulted in increased hardened air content. Hardened air content after 120 minutes ranged from 3.3 to 4.6 percent.

- The average 28-day compressive strengths of all mixtures evaluated in Task 2 exceeded 5000 psi. Increased transit time resulted in an average increase in 28-day compressive strength of 155 psi, which is probably not a statistically significant difference.
- The durability factors of all mixtures evaluated were in the range of 83 – 87, which is considered very good. There was no apparent effect of transit time on durability factor.
- The dilations (freeze-thaw testing) of all mixtures evaluated were 0.03 to 0.04, which is considered good. There was no apparent effect of transit time on dilation.

Table 30. Summary of Gross Test Result Averages for Task 2

	Average	Range	Std. Dev.
Slump, in			
t = 60	5.69	4.50 – 6.50	0.99
t = 120	3.94	3.00 – 5.00	0.97
Δ (t = 60 to t = 120)	-1.75	-2.00 – -1.50	0.29
Plastic Air Content, %			
t = 60	6.63	5.60 – 7.70	0.95
t = 120	6.28	5.50 – 6.80	0.55
Δ (t = 60 to t = 120)	-0.35	-0.90 – 0.80	0.78
Hardened Air Content,%			
t = 60	4.60	3.70 – 6.00	0.98
t = 120	4.15	3.30 – 4.60	0.61
Δ (t = 60 to t = 120)	-0.45	-1.45 – 0.90	1.01
f’c (28-day), psi			
t = 60	5633	5430 - 5790	151
t = 120	5788	5240 - 6200	406
Δ (t = 60 to t = 120)	155	-440 - 510	426
DF			
t = 60	86.0	83.5 – 87.5	2.18
t = 120	85.0	84.5 – 86.0	0.87
Δ (t = 60 to t = 120)	-1.0	-2.5 – 1.0	1.80
Dilation, %			
t = 60	0.03	0.03 – 0.04	0.003
t = 120	0.03	0.03	0
Δ (t = 60 to t = 120)	0.00	-0.01 – 0	0.003

In summary, analysis of the data from Task 2 tests indicates that increased transit time from 60 to 120 minutes resulted in an average loss of slump of 1.75 inches, along with minor losses of plastic and hardened air content (about 0.4 percent). The use of 35 percent slag cement (rather than 20 percent fly ash) appeared to increase plastic air content for both transit times and increased hardened air content for the 60-minute transit time. The use of increased total cementitious content provided a slight increase in plastic air content at 120 minutes transit time and a slight decrease in hardened air content at 60 minutes transit time. Neither cementitious content nor SCM type/replacement level appeared to have significant effects on concrete durability at either transit time in this study.

5.2.3 Task 3

The fourteen runs that comprise the regional testing program comprise seven sets of two runs (one each of two different mixture designs) implemented at seven different ready-mix plants. For the purposes of this analysis, it is assumed that the two mixtures (MnDOT 3A32 and 3Y43) are identical at each of the seven plants so that the only real variable is mixture design. In reality, there are slight differences in mixture proportions at several of the plants and it is certain that different component materials are used at each of the plants. However, this design of this task is sufficient for measuring the variability in test results for producing these two mixtures at several locations.

The primary outputs of interest (dependent variables) are assumed to be slump, plastic air content, hardened air content, 28-day compressive strength, durability factor, dilation and mass loss. The effects of changing the overall mixture design (from 3A32 to 3Y43) on each of these test results are described below.

Table 31 summarizes the gross averages of the test results for the Task 3 batches. The following observations can be drawn from this table:

- The loss of slump that resulted from the increasing transit time from 60 minutes to 120 minutes averaged 1.7 inches and was as high as 3.5 inches. Actual slump values at 120 minutes averaged 3.5 inches, but ranged from 0.5 to 8.8 inches.
- The loss of plastic air that resulted from increasing transit time from 60 to 120 minutes averaged 1.3 percent. In one case, the added transit time resulted in increased air. Plastic air content after 120 minutes averaged 5.0 percent and ranged from 3.0 to 7.5 percent.
- The loss of hardened air that resulted from increasing transit time averaged 1.2 percent. Hardened air content after 120 minutes averaged 4.2 percent and ranged from 2.4 to 6.7 percent.
- The average 28-day compressive strengths of all mixtures evaluated in Task 3 exceeded 5500 psi, although the 3A32 mixture at Duluth Ready Mix had 28-day strengths of less than 4000 psi for both transit times. Increased transit time resulted in an average increase in 28-day compressive strength of 286 psi, which is probably not a statistically significant difference.
- The durability factors of all mixtures evaluated were in the range of 83 – 93, which is considered very good. There was no apparent effect of transit time on durability factor.
- The dilations (freeze-thaw testing) of all mixtures evaluated were 0.02 to 0.04, which is considered good. There was no apparent effect of transit time on dilation.

Table 31. Summary of Gross Test Result Averages for Task 3

	Average	Range	Std. Dev.
Slump, in			
t = 60	5.2	1.3 – 9.0	2.48
t = 120	3.5	0.5 – 8.8	2.66
Δ (t = 60 to t = 120)	-1.7	-3.5 – 0.3	0.82
Plastic Air Content, %			
t = 60	6.3	3.7 – 8.2	1.65
t = 120	5.0	3.0 – 7.5	1.42
Δ (t = 60 to t = 120)	-1.2	-2.9 – 1.5	1.07
Hardened Air Content,%			
t = 60	5.5	3.0 – 8.4	1.72
t = 120	4.2	2.4 – 6.7	1.35
Δ (t = 60 to t = 120)	-1.2	-3.0 – 0.2	1.06
f'c (28-day), psi			
t = 60	5589	3220 - 8080	1484
t = 120	5874	3970 - 7710	1172
Δ (t = 60 to t = 120)	286	-570 - 1480	644
DF			
t = 60	89.1	83.5 – 93.0	2.86
t = 120	88.8	85.5 – 93.0	2.14
Δ (t = 60 to t = 120)	-0.4	-3.5 – 3.5	2.05
Dilation, %			
t = 60	0.03	0.02 – 0.03	0.004
t = 120	0.03	0.03	0.001
Δ (t = 60 to t = 120)	0.00	0.00 – 0.01	0.003

In summary, analysis of the data from Task 3 tests indicates that:

- The use of 3Y43 mixture designs (rather than 3A32) resulted in increased slump values (about 1.6 inches) at both transit times, but had no significant effect on plastic air, hardened air, 28-day compressive strength, durability factor or dilation. Which corresponds to the fact that 3Y43 has a design slump of 5 inches and 3A32 has a design slump of 4 inches with a water reducer.
- The loss of slump that resulted from increasing the transit time from 60 minutes to 120 minutes averaged 1.7 inches and was as high as 3.5 inches.
- The loss of plastic air that resulted from increasing transit time from 60 to 120 minutes averaged 1.3 percent.
- The loss of hardened air that resulted from increasing transit time averaged 1.2 percent.
- The average 28-day compressive strengths of all mixtures evaluated in Task 3 exceeded 5500 psi, although there was significant variability in compressive strength at the seven test sites and one batch had 28-day strengths of less than 4000 psi for both transit times.
- The durability factors of all mixtures evaluated were in the range of 83 – 93, which is considered very good. There was no apparent effect of transit time on durability factor.

- The dilations (freeze-thaw testing) of all mixtures evaluated were 0.02 to 0.04, which is considered good. There was no apparent effect of transit time on dilation.

CHAPTER 6. CALORIMETRY TESTING

6.1 Background

An additional aspect of this study included the use of calorimetry to study the performance of various combinations of cement, ash, and admixtures to see the effect upon the various cement and cementitious combinations. Calorimetry is the monitoring of heat generation from hydration and can be used to evaluate various performance characteristics including setting time, early strength, slump behavior, and potential material combination "incompatibilities."

6.2 Procedure

Mixtures were monitored for a 24-hour time period. Within this study, two forms of calorimetry were used to evaluate select combinations.

The first method was semi-adiabatic calorimetry using a 16 channel ThermoCal system from Solidus Integration, which uses probes to monitor changes in temperature over time as well as ambient temperature.

The second calorimetry method used was an isothermal calorimetry system Adiacal TC, which monitors the amount of energy required to maintain a constant temperature of the sample. This system can be used to keep constant temperatures as various presets (i.e. 73 º F and 90 º F). One of the benefits of this system is that it will generally show important, but minor, nuances in the curves, such as sulfate depletion marks and C3A reactions in the first few minutes, that would not otherwise generally show up as well in semi-adiabatic calorimetry. Combinations were evaluated at both 73 º F and 90 º F presets.

The proportions used for each set were similar, and were the following:

Total Cementitious - 700 g
Water Cementitious Ratio - 0.43
Admixtures dosed to total cementitious material.

- Batching Procedure
  - Mixes were batched in bowl with a kitchen hand mixer.
  - Admixtures were added to the batch water ahead of time and then added to the cementitious materials.
  - The batch was mixed for 60 seconds.
  - The mixture was transferred into the calorimetry vessel, which took roughly 30 seconds.

All calorimetry work was performed at the Holcim (US) Inc. Concrete Laboratory, which is located at the St. Genevieve cement plant in Bloomsdale, MO.

6.3 Observations

From the data, the following generic observations were noted. Note that more specific observations may be made by using the calorimetry curves shown in Appendices F and G.

1. In the vast majority of the combinations and scenarios observed, the curve behavior is described as normal behavior. The effect of the Supplementary Cementitious Materials (SCMs) and admixtures on the curves appeared to be reasonable.
2. The effect of mix variations (fly ash, admixtures) upon the calorimetry curves tended to be unique to the combination. In other words, the effect of one fly ash or admixture on one cementitious system did not necessarily effect another cementitious combination to the same magnitude. This situation is typical in these evaluations, which is why calorimetry provides a benefit in being able to evaluate many combinations of materials in a short time period.
3. In some of the combinations, there were several examples that mimic a less-than-optimized sulfate–C3A balance; however, there were no combinations that showed excessive flash set characteristics. This type of behavior would typically be exhibited by a large, sharp early peak followed by a dormancy period that lasts an extended period, sometimes for days.
4. The increase use of SCMs tended to extend the curves (retarding effect). The use of admixtures also tended to extend the curves and, in many cases, had a greater effect than SCM use. Some combinations using higher dosages of water reducers/retarders exhibited significant retarding effects.

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Background

The goal of this project was to utilize the results of the testing programs and develop specification guidelines that allow the implementation of chemical admixtures to extend transport and delivery time from the current 60 minutes for air-entrained concrete up to 120 minutes.

7.2 Conclusions

The statistical evaluations showed the following:

- There is a drop in plastic and hardened air content when extending the transit time from 60 minutes to 120 minutes; 1.3 percent and 1.2 percent, respectively.
- There is a significant loss of slump with an average loss of 1.7 inches.
- There was not a significant effect on concrete compressive strength by extending the transit time.
- There was not a significant effect on freeze-thaw durability by extending the transit time.

7.3 Recommendations

Based upon the test results, it is apparent that there are no performance related issues directly related to the use of retarding and water reducer admixtures, beyond the loss of slump and air content.

We recommend the following additions to MnDOT Specification 2461 as a Special Provision:

- In any case, do not add additional mixing water once the concrete is 60 minutes old. Only provide admixture additions at the job site that are the same products as originally incorporated into the mix. Mix the load a minimum of 5 minutes or 50 revolutions at mixing speed after addition of the admixture.
- To extend the delivery time to 90 minutes allow the Contractor to use a retarding admixture at the manufacturer's recommended dosage rates provided all admixtures are initially mixed into the concrete at the plant.
- To extend the delivery time to 120 minutes, the Contractor shall provide the following once per each mix per each combination of materials:
  - Contractor mix design allowing up to 20% fly ash replacement for cement and the use of any necessary admixtures as recommended by the admixture manufacturer in order to meet the required compressive strength for that Grade of concrete.
  - Field trial batching on the proposed mix (minimum of 5 cubic yard batch size) utilizing the same materials, mixing and transporting procedures as will be used for supplying the concrete.
  - The ready mix truck drum should maintain a minimum 6 revolution spin between sampling for the entire 120 minutes.
  - Testing on slump, air content, unit weight and temperature immediately after batching and at 90 and 120 minutes.

- Compressive strength testing at 90 and 120 minutes (sets of 3).
- Hardened air content (ASTM C457) at a minimum of 7 days (5 samples). The Contractor is required to test at least 1 sample and provide MnDOT with the other 4 samples for informational testing at their discretion.

APPENDIX A: TASK 1 – LABORATORY TEST RESULT

Table A1

Mix Proportions (SSD)

Batch #1	Design	Adjusted Weights*
Cement 2, pcy	414	416
Fly Ash 1, pcy	103 (20%)	104 (20%)
3/4" Gravel, pcy	1,818	1,827
Concrete Sand, pcy	1,331	1,338
Water, pcy	223	224
Water Cementitious Ratio	.43	.43

Batch #2	Design	Adjusted Weights*
Cement 2, pcy	414	415
Fly Ash 2, pcy	103 (20%)	103 (20%)
3/4" Gravel, pcy	1,818	1,822
Concrete Sand, pcy	1,331	1,334
Water, pcy	223	224
Water Cementitious Ratio	.43	.43

Batch #3	Design	Adjusted Weights*
Cement 2, pcy	414	416
Fly Ash 1, pcy	103 (20%)	104 (20%)
3/4" Gravel, pcy	1,818	1,827
Concrete Sand, pcy	1,331	1,338
Water, pcy	223	224
Water Cementitious Ratio	.43	.43

Batch #4	Design	Adjusted Weights*
Cement 2, pcy	414	417
Fly Ash 2, pcy	103 (20%)	104 (20%)
3/4" Gravel, pcy	1,818	1,829
Concrete Sand, pcy	1,331	1,339
Water, pcy	223	224
Water Cementitious Ratio	.43	.43

*Adjusted weights are based on actual measured weights of each material and the unit weight of the plastic concrete.

Batch #5	**Design**	**Adjusted Weights***
Cement 1, pcy	414	416
Fly Ash 1, pcy	103 (20%)	104 (20%)
3/4" Gravel, pcy	1,818	1,827
Concrete Sand, pcy	1,331	1,338
Water, pcy	223	224
Water Cementitious Ratio	.43	.43

Batch #6	**Design**	**Adjusted Weights***
Cement 1, pcy	414	415
Fly Ash 2, pcy	103 (20%)	103 (20%)
3/4" Gravel, pcy	1,818	1,822
Concrete Sand, pcy	1,331	1,334
Water, pcy	223	224
Water Cementitious Ratio	.43	.43

Batch #7	**Design**	**Adjusted Weights***
Cement 1, pcy	414	416
Fly Ash 1, pcy	103 (20%)	104 (20%)
3/4" Gravel, pcy	1,818	1,826
Concrete Sand, pcy	1,331	1,337
Water, pcy	223	224
Water Cementitious Ratio	.43	.43

Batch #8	**Design**	**Adjusted Weights***
Cement 1, pcy	414	417
Fly Ash 2, pcy	103 (20%)	104 (20%)
3/4" Gravel, pcy	1,818	1,829
Concrete Sand, pcy	1,331	1,339
Water, pcy	223	224
Water Cementitious Ratio	.43	.43

Batch #9	**Design**	**Adjusted Weights***
Cement 1, pcy	414	415
Fly Ash 1, pcy	103 (20%)	103 (20%)
3/4" Gravel, pcy	1,818	1,822
Concrete Sand, pcy	1,331	1,334
Water, pcy	223	224
Water Cementitious Ratio	.43	.43

*Adjusted weights are based on actual measured weights of each material and the unit weight of the plastic concrete.

Batch #10	**Design**	**Adjusted Weights***
Cement 1, pcy	414	415
Fly Ash 2, pcy	103 (20%)	103 (20%)
3/4" Gravel, pcy	1,818	1,822
Concrete Sand, pcy	1,331	1,334
Water, pcy	223	224
Water Cementitious Ratio	.43	.43

Batch #11	**Design**	**Adjusted Weights***
Cement 1, pcy	414	416
Fly Ash 1, pcy	103 (20%)	104 (20%)
3/4" Gravel, pcy	1,818	1,827
Concrete Sand, pcy	1,331	1,338
Water, pcy	223	224
Water Cementitious Ratio	.43	.43

Batch #12	**Design**	**Adjusted Weights***
Cement 1, pcy	414	415
Fly Ash 2, pcy	103 (20%)	103 (20%)
3/4" Gravel, pcy	1,818	1,822
Concrete Sand, pcy	1,331	1,334
Water, pcy	223	224
Water Cementitious Ratio	.43	.43

Batch #13	**Design**	**Adjusted Weights***
Cement 3, pcy	414	409
Fly Ash 1, pcy	103 (20%)	102 (20%)
3/4" Gravel, pcy	1,818	1,797
Concrete Sand, pcy	1,331	1,316
Water, pcy	223	221
Water Cementitious Ratio	.43	.43

Batch #14	**Design**	**Adjusted Weights***
Cement 3, pcy	414	408
Fly Ash 2, pcy	103 (20%)	102 (20%)
3/4" Gravel, pcy	1,818	1,792
Concrete Sand, pcy	1,331	1,312
Water, pcy	223	220
Water Cementitious Ratio	.43	.43

*Adjusted weights are based on actual measured weights of each material and the unit weight of the plastic concrete.

Batch #15	Design	Adjusted Weight*
Cement 1, pcy	414	407
Fly Ash 1, pcy	103 (20%)	101 (20%)
3/4" Gravel, pcy	1,818	1,787
Concrete Sand, pcy	1,331	1,308
Water, pcy	223	219
Water Cementitious Ratio	.43	.43

Batch #16	Design	Adjusted Weights*
Cement 1, pcy	414	408
Fly Ash 2, pcy	103 (20%)	102 (20%)
3/4" Gravel, pcy	1,818	1,792
Concrete Sand, pcy	1,331	1,312
Water, pcy	223	220
Water Cementitious Ratio	.43	.43

Batch #17	Design	Adjusted Weights*
Cement 1, pcy	414	410
Fly Ash 3, pcy	103 (20%)	102 (20%)
3/4" Gravel, pcy	1,818	1,802
Concrete Sand, pcy	1,331	1,306
Water, pcy	223	221
Water Cementitious Ratio	.43	.43

Batch #18	Design	Adjusted Weights*
Cement 1, pcy	414	406
Fly Ash 1, pcy	103 (20%)	101 (20%)
3/4" Gravel, pcy	1,818	1,785
Concrete Sand, pcy	1,331	1,307
Water, pcy	223	219
Water Cementitious Ratio	.43	.43

Batch #19	Design	Adjusted Weights*
Cement 1, pcy	414	406
Fly Ash 2, pcy	103 (20%)	101 (20%)
3/4" Gravel, pcy	1,818	1,782
Concrete Sand, pcy	1,331	1,305
Water, pcy	223	219
Water Cementitious Ratio	.43	.43

*Adjusted weights are based on actual measured weights of each material and the unit weight of the plastic concrete.

Batch #20	**Design**	**Adjusted Weights***
Cement 1, pcy	414	407
Fly Ash 1, pcy	103 (20%)	101 (20%)
3/4" Gravel, pcy	1,818	1,787
Concrete Sand, pcy	1,331	1,308
Water, pcy	223	219
Water Cementitious Ratio	.43	.43

Batch #21	**Design**	**Adjusted Weights***
Cement 1, pcy	414	416
Fly Ash 3, pcy	103 (20%)	104 (20%)
3/4" Gravel, pcy	1,818	1,827
Concrete Sand, pcy	1,331	1,338
Water, pcy	223	224
Water Cementitious Ratio	.43	.43

Batch #22	**Design**	**Adjusted Weights***
Cement 2, pcy	414	407
Fly Ash 1, pcy	103 (20%)	101 (20%)
3/4" Gravel, pcy	1,818	1,787
Concrete Sand, pcy	1,331	1,308
Water, pcy	223	219
Water Cementitious Ratio	.43	.43

Batch #23	**Design**	**Adjusted Weights***
Cement 2, pcy	414	410
Fly Ash 3, pcy	103 (20%)	102 (20%)
3/4" Gravel, pcy	1,818	1,802
Concrete Sand, pcy	1,331	1,306
Water, pcy	223	221
Water Cementitious Ratio	.43	.43

*Adjusted weights are based on actual measured weights of each material and the unit weight of the plastic concrete.

Table A2. Task 1 Compressive Strengths

Lab comps I=initially cast; F-Final cast or 120 minutes
Two beams were cast initially and two beams were cast after 120 minutes

Batch No. 1	1-Day	7-Day	28-Day
1I	2270	4380	5670
1I	2190	4580	5840
1F	1780	4200	5940
1F	1700	4390	6010
2I	1830	3940	6130
2I	1770	4020	5720
2F	1630	4160	5920
2F	1710	4480	6300
3I	2260	4080	5590
3I	2200	4170	5740
3F	2000	4210	6290
3F	2000	4250	5980
4I	2010	4730	7110
4I	2190	4890	6440
4F	1760	4290	6090
4F	1880	4490	6160
5I	1660	4050	5680
5I	1600	3990	5550
5F	1590	4080	6130
5F	1530	4310	6100
6I	1120	4040	6020
6I	1160	4090	6350
6F	1140	4230	6150
6F	1100	4220	5870
7I	1400	3990	5950
7I	1340	4300	5760
7F	1260	4520	6050
7F	1300	4330	6050
8I	1240	4840	6470
8I	1240	4310	6610
8F	1230	4760	6760
8F	1270	4340	6870
9I	2030	5280	6250
9I	2450	5100	6180
9F	1640	3600	4610
9F	1700	3650	4700
10I	2560	5240	6670
10I	2500	4630	6730
10F	1550	3540	4700
10F	1610	3540	4860

Batch No. 1	1-Day	7-Day	28-Day
11I	2490	4960	6040
11I	2530	4790	5800
11F	1930	3870	5030
11F	1750	3660	4990
12I	2120	4610	6000
12I	2580	4720	5950
12F	1900	3970	5470
12F	1780	4110	5350
13I	2020	3810	5420
13I	2200	4010	5420
13F	1690	3300	4590
13F	1570	3300	4900
14I	2310	4110	5610
14I	2150	3990	5870
14F	2220	4100	5980
14F	1980	4100	5980
15I	2020	3700	4620
15I	2000	3810	4930
15F	2030	3770	5180
15F	2010	3770	5550
16I	2300	4200	5850
16I	2280	3920	5850
16F	2370	4140	5720
16F	2250	4140	5670
17I	2420	4630	5390
17I	2360	4840	5510
17F	2270	3630	4670
17F	2330	3630	5140
18I	2120	3440	4390
18I	2160	3880	4390
18F	2010	3900	4830
18F	2030	3880	4730
19I	2310	4040	4800
19I	2190	4140	4700
19F	2300	4700	5530
19F	2340	4690	5640
20I	2100	3230	4570
20I	2300	3390	4870
20F	1800	3440	4220
20F	1680	3230	3990
21I	2600	5540	6650
21I	2480	5570	6530
21F	2610	4690	5510
21F	2430	4760	5410

Batch No. 1	1-Day	7-Day	28-Day
22I	2020	3830	5600
22I	1960	4100	5220
22F	2250	4430	5510
22F	2310	4150	5280
23I	2180	4210	6070
23I	2400	4350	6070
23F	1810	4010	5260
23F	1890	4060	5420
Average Initial	2060	4280	5730
Average Final	1790	3960	5380

Table A3. Task #1 Freeze-Thaw Results Initial (Average of Two Samples)

Cycles		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
32	Weight, loss %	.05	.04	.05	.03	.00	.03	.05	.02	.04	.05	.04	.06	.05	.03	.06	.04	.05	.03	.02	.00	.03	.02	.05
	Length, Exp. %	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
	RDM, %	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	99	100	100
68	Weight, loss %	.10	.10	.09	.08	.10	.10	.10	.08	.11	.08	.09	.11	.10	.13	.12	.09	.11	.13	.09	.07	.09	.15	.10
	Length, Exp. %	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
	RDM, %	99	99	99	99	99	99	99	99	99	99	98	99	99	99	99	99	99	99	99	99	99	99	99
100	Weight, loss %	.11	.12	.15	.15	.10	.13	.13	.12	.20	.25	.14	.18	.17	.18	.17	.15	.17	.24	.17	.09	.13	.23	.13
	Length, Exp. %	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
	RDM, %	97	98	97	97	98	98	97	98	97	97	98	97	97	98	98	98	98	98	98	97	98	98	98
132	Weight, loss %	.18	.25	.26	.21	.17	.19	.18	.16	.34	.33	.24	.26	.28	.26	.24	.21	.22	.31	.29	.21	.19	.29	.21
	Length, Exp. %	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01
	RDM, %	95	96	95	96	96	96	95	97	96	95	96	95	95	97	96	97	97	96	98	95	97	96	97
171	Weight, loss %	.22	.27	.29	.27	.25	.24	.25	.22	.40	.37	.33	.29	.30	.37	.33	.34	.31	.42	.46	.36	.29	.37	.32
	Length, Exp. %	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01
	RDM, %	95	94	93	95	95	95	95	96	94	95	95	95	94	95	95	96	96	95	96	95	96	94	96
208	Weight, loss %	.25	.30	.39	.36	.34	.28	.36	.31	.45	.42	.51	.33	.36	.43	.41	.44	.42	.50	.58	.43	.50	.50	.55
	Length, Exp. %	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01
	RDM, %	94	93	92	93	93	94	94	95	93	92	94	94	93	94	94	95	95	94	95	94	94	93	95
240	Weight, loss %	.29	.41	.52	.42	.39	.38	.43	.39	.56	.51	.58	.48	.47	.52	.48	.53	.49	.62	.71	.56	.61	.62	.66
	Length, Exp. %	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02
	RDM, %	94	92	91	92	92	94	94	94	92	91	94	93	91	93	93	93	93	93	94	92	93	92	94
271	Weight, loss %	.33	.52	.63	.58	.55	.50	.52	.43	.62	.63	.69	.64	.56	.63	.61	.65	.59	.75	.89	.68	.73	.75	.72
	Length, Exp. %	.02	.02	.02	.02	.02	.02	.02	.02	.03	.02	.02	.02	.02	.02	.02	.02	.02	.03	.02	.02	.02	.02	.02
	RDM,%	93	92	90	90	90	93	93	93	91	90	92	90	90	92	92	91	92	91	92	90	91	90	93
300	Weight, loss %	.41	.66	.76	.75	.70	.68	.61	.56	.67	.69	.75	.79	.69	.71	.68	.77	.70	1.27	.96	.72	.86	.81	.89
	Length, Exp. %	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03
	RDM, %	92	91	88	88	88	91	92	91	90	89	90	88	89	90	91	90	91	89	90	89	89	88	91
	Durability Factor	92	91	88	88	88	91	92	91	90	89	90	88	89	90	91	90	91	89	90	89	89	88	91

Table A4. Task #1 Freeze-Thaw Results Final 120 Minutes (Average of Two Samples)

Cycles		1.1	2.1	3.1	4.1	5.1	6.1	7.1	8.1	9.1	10.1	11.1	12.1	13.1	14.1	15.1	16.1	17.1	18.1	19.1	20.1	21.1	22.1	23.1
34	Weight, loss %	.00	.02	.01	-.02	.02	.02	.04	.04	.02	.00	.03	.04	.04	.04	.05	.00	.02	.01	.04	.03	.05	.06	.04
	Length, Exp. %	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
	RDM, %	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
70	Weight, loss %	.03	.05	.04	.03	.08	.13	.11	.09	.09	.06	.10	.11	.12	.10	.10	.07	.11	.09	.11	.11	.12	.18	.10
	Length, Exp. %	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
	RDM, %	99	99	99	100	99	99	99	99	100	100	99	99	100	99	99	100	100	100	99	99	100	100	100
102	Weight, loss %	.12	.10	.16	.08	.12	.18	.16	.15	.19	.17	.12	.15	.16	.15	.19	.17	.19	.19	.20	.19	.15	.28	.16
	Length, Exp. %	.00	.00	.01	.00	.01	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
	RDM, %	96	97	96	98	97	98	98	97	98	98	97	98	98	97	97	98	99	98	98	98	99	98	98
136	Weight, loss %	.21	.19	.27	.18	.18	.23	.21	.18	.29	.29	.21	.23	.25	.23	.25	.23	.25	.33	.33	.23	.21	.34	.23
	Length, Exp. %	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01
	RDM, %	94	95	94	96	95	96	97	95	98	96	95	97	97	95	95	97	97	96	97	96	97	96	96
177	Weight, loss %	.30	.27	.36	.28	.20	.28	.28	.24	.39	.38	.30	.31	.31	.33	.36	.35	.33	.49	.49	.38	.30	.43	.38
	Length, Exp. %	.02	.01	.02	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01
	RDM, %	94	94	92	94	95	94	95	94	96	94	93	96	95	93	93	95	95	94	95	94	95	95	94
213	Weight, loss %	.38	.36	.42	.33	.29	.32	.40	.36	.46	.43	.49	.34	.33	.39	.46	.46	.46	.53	.60	.47	.52	.50	.58
	Length, Exp. %	.02	.02	.02	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.02	.02	.02	.01	.02	.01	.01	.01	.01	.02
	RDM, %	93	92	90	93	93	92	93	93	94	92	92	94	93	91	93	93	93	93	93	94	93	93	93
241	Weight, loss %	.42	.44	.53	.40	.36	.40	.43	.40	.58	.49	.55	.44	.49	.55	.49	.57	.48	.64	.78	.58	.68	.69	.68
	Length, Exp. %	.02	.02	.02	.01	.01	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02
	RDM, %	91	92	89	92	91	91	92	92	92	91	91	92	92	90	91	91	91	92	90	92	92	91	92
272	Weight, loss %	.46	.58	.69	.53	.43	.51	.55	.46	.69	.59	.64	.62	.52	.68	.62	.68	.62	.70	.92	.73	.75	.80	.78
	Length, Exp. %	.02	.03	.03	.02	.02	.03	.02	.02	.03	.02	.02	.02	.02	.02	.03	.03	.03	.03	.03	.02	.02	.02	.02
	RDM,%	91	90	88	90	90	90	92	91	90	89	90	90	90	89	90	90	90	90	90	90	91	90	91
303	Weight, loss %	.50	.62	.79	.69	.62	.70	.62	.57	.73	.65	.73	.72	.62	.78	.70	.79	.75	.86	1.00	.75	.88	.85	.90
	Length, Exp. %	.03	.03	.03	.02	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03
	RDM, %	90	88	87	88	88	89	90	90	89	88	89	89	88	87	89	89	90	89	88	89	89	89	89
	Durability Factor	90	88	87	88	88	89	90	90	89	88	89	89	88	87	89	89	90	89	88	89	89	89	89

APPENDIX B: TASK 2 – CONTROLLED PLANT MIXING PROGRAM TEST RESULTS

Table B1. Plastic Testing Results (Task 2)

Ambient Temperature - 78° F, Sunny

Batch #1-3A32F

Time	Slump, in.	Air, %	Unit Weight, lb/ft3	Temperature, F
Initial	7	7.3	144.8	80
30 Minutes	5.75	6.7	145.2	80
60 Minutes	4.5	6.1	146.8	80
90 Minutes	4.5	5.5	146	82
120 Minutes	3	5.5	146.8	86

Batch #2-3A32S

Time	Slump, in.	Air, %	Unit Weight, lb/ft3	Temperature, F
Initial	7.75	7.1	144.8	75
30 Minutes	6.75	6.9	144.8	78
60 Minutes	5.25	7.1	143.2	83
90 Minutes	4.25	7.0	145.2	84
120 Minutes	3.25	6.4	145.6	87

Batch #3-3Y43F

Time	Slump, in.	Air, %	Unit Weight, lb/ft3	Temperature, F
Initial	8.5	6.1	144.0	80
30 Minutes	7.0	5.9	146.0	82
60 Minutes	6.5	5.6	146.4	80
90 Minutes	6	6.2	144.0	81
120 Minutes	5	6.4	144.0	83

Batch #4-3Y43S

Time	Slump, in.	Air, %	Unit Weight, lb/ft3	Temperature, F
Initial	7.75	8.0	141.2	78
30 Minutes	7.0	7.6	142.8	79
60 Minutes	6.5	7.7	142.4	81
90 Minutes	5.0	7.1	143.2	82
120 Minutes	4.5	6.8	143.6	86

Table B2. Compressive Strength Results, psi (Task 2)

Batch No.	60 min.	90 min.	120 min.
1	5640	5690	5910
1	5210	5950	5960
2	5510	5600	5630
2	5750	5380	5900
3	5640	4490	5270
3	5720	5310	5210
4	5810	6200	6200
4	5750	6040	6200

Table B3. Task #2 Freeze-Thaw Results

Cycles		1A-60	1B-60	1A-120	1B-120	2A-60	2B-60	2A-120	2B-120	3A-60	3B-60	3A-120	3B-120
29	Weight, loss %	.03	.03	.05	.04	.03	.04	.02	.03	.00	.02	.03	.04
	Length, Exp. %	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
	RDM, %	100	100	100	100	100	100	100	100	100	100	100	100
64	Weight, loss %	.10	.08	.11	.12	.08	.09	.10	.09	.06	.08	.09	.12
	Length, Exp. %	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
	RDM, %	98	98	100	99	97	98	98	98	98	97	98	98
97	Weight, loss %	.18	.17	.20	.22	.12	.15	.17	.18	.12	.10	.19	.21
	Length, Exp. %	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
	RDM, %	97	98	98	97	94	95	96	95	96	95	96	95
130	Weight, loss %	.24	.21	.25	.28	.18	.22	.24	.26	.23	.28	.24	.26
	Length, Exp. %	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01
	RDM, %	95	96	96	95	93	92	94	92	94	93	93	92
175	Weight, loss %	.34	.32	.38	.40	.43	.41	.43	.46	.38	.38	.36	.41
	Length, Exp. %	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01
	RDM, %	92	92	91	93	90	91	93	90	92	92	92	91
205	Weight, loss %	.48	.46	.51	.55	.62	.65	.56	.61	.43	.46	.49	.55
	Length, Exp. %	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02
	RDM, %	91	91	90	91	88	89	91	89	91	90	90	89
238	Weight, loss %	.55	.57	.61	.68	.73	.78	.68	.75	.55	.55	.58	.70
	Length, Exp. %	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02
	RDM, %	89	90	89	90	86	88	90	87	89	89	88	87
274	Weight, loss %	.75	.79	.83	.90	.89	.84	.75	.82	.75	.77	.75	.92
	Length, Exp. %	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03
	RDM, %	88	90	88	88	84	86	89	83	88	88	86	86
301	Weight, loss %	.87	.92	.96	1.03	1.11	.99	.87	.92	.87	.91	.97	1.13
	Length, Exp. %	.03	.03	.03	.03	.04	.03	.03	.03	.03	.03	.03	.03
	RDM, %	87	88	86	86	82	85	87	82	87	87	84	85
	Durability Factor %	87	88	86	86	82	85	87	82	87	87	84	85

APPENDIX C: TASK 3 – REGIONAL CONCRETE TESTING RESULTS

Task #3
(Regional Testing/Hardened Air/ Freeze-Thaw)
MnDOT CONCRETE DELIVERY TIME STUDY
Plant #1: Rochester Ready Mix - August 19, 2010
Mix Proportions (SSD)

Batch #5- 3A32	Mix Design	Adjusted Weights
Cement, pcy	448	444
Fly Ash, pcy	112 (20%)	111 (20%)
3/4" Limestone, pcy	1,796	1,779
Concrete Sand, pcy	1,285	1,273
Water, pcy	252	250
Water Cementitious Ratio	.45	.45

Batch #6- 3Y43	Mix Design	Adjusted Weights
Cement, pcy	512	502
Fly Ash, pcy	128 (20%)	126 (20%)
3/4" Limestone, pcy	1,770	1,736
Concrete Sand, pcy	1,144	1,122
Water, pcy	288	283
Water Cementitious Ratio	.45	.45

Plastic Testing Results

Ambient Temperature, 77° F, Overcast, windy

Table C1. Batch #5-3A32

Time	Slump, in.	Air, %	Unit Weight, lb/ft^3	Temperature, F
Initial	7.5	7.5	142.8	77
30 Minutes	6.75	7.2	144.0	78
60 Minutes	5.0	6.8	145.6	82
90 Minutes	4.75	5.8	146	84
120 Minutes	3.25	5.2	147.2	85

Table C2. Batch #6-3Y43

Time	Slump, in.	Air, %	Unit Weight, lb/ft^3	Temperature, F
Initial	8.75	8.0	139.6	75
30 Minutes	8.0	7.8	140.4	76
60 Minutes	7.5	7.3	141.2	78
90 Minutes	7.0	6.5	143.2	80
120 Minutes	6.0	6.0	143.2	82

Table C3. Compressive Strength Results, psi

Batch #	60 minutes*	90 Minutes*	120 Minutes*
5	5570	5420	5450
6	5070	5080	4830

* Average of 2 cylinders

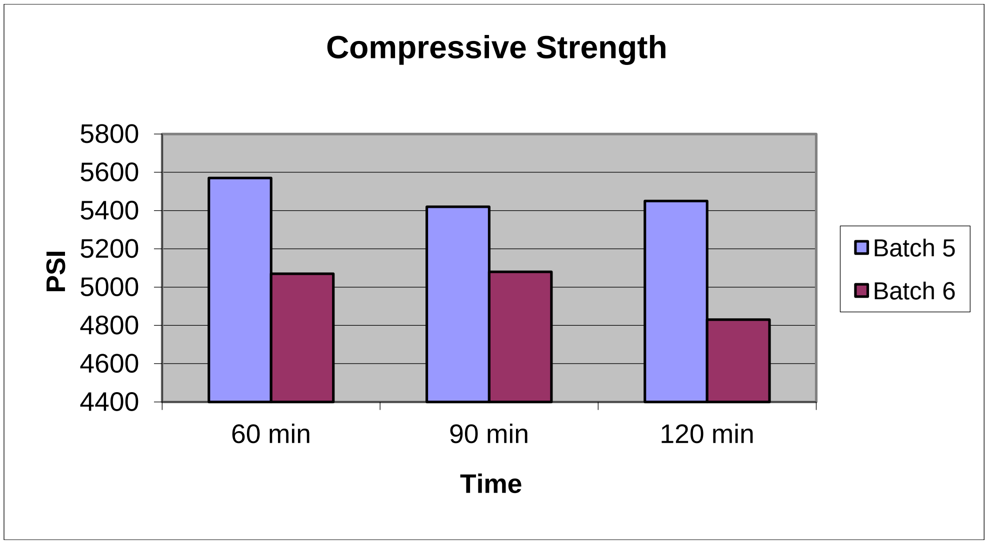


Figure C1. Compressive Strength

Table C4. Hardened Air (%)

Batch No.	60 min	120 min
5	4.5	3.7
6	6.8	4.6
Average	**5.7**	**4.2**

Table C5. Freeze-Thaw Results

Cycles		5A-60	5B-60	5A-120	5B-120	6A-60	6B-60	6A-120	6B-120
32	Weight, loss % Length, Exp. % RDM, %	-.02 .00 99	.00 .00 100	.00 .00 100	-.01 .00 99	.02 .00 100	.00 .00 99	.01 .00 100	-.02 .00 100
68	Weight, loss % Length, Exp. % RDM, %	.12 .00 98	.13 .00 99	.13 .00 99	.11 .00 98	.09 .00 99	.12 .00 98	.14 .00 98	.15 .00 99
100	Weight, loss % Length, Exp. % RDM, %	.24 .01 94	.25 .01 97	.20 .01 97	.18 .01 97	.18 .01 97	.22 .01 96	.25 .01 96	.29 .01 97
132	Weight, loss % Length, Exp. % RDM, %	.30 .01 91	.31 .01 92	.33 .01 96	.29 .01 96	.29 .01 95	.32 .01 94	.35 .01 95	.38 .01 95
171	Weight, loss % Length, Exp. % RDM, %	.44 .02 92	.46 .02 89	.45 .02 95	.39 .02 96	.36 .02 93	.41 .02 93	.45 .02 92	.51 .02 92
208	Weight, loss % Length, Exp. % RDM, %	.62 .02 90	.65 .02 87	.60 .02 94	.55 .02 94	.53 .02 90	.55 .02 91	.62 .02 90	.65 .02 90
240	Weight, loss % Length, Exp. % RDM, %	.67 .02 89	.71 .02 85	.68 .02 92	.63 .03 93	.70 .02 87	.75 .02 88	.78 .02 89	.76 .02 88
271	Weight, loss % Length, Exp. % RDM, %	.72 .02 88	.75 .03 85	.76 .03 90	.72 .03 91	.86 .03 85	.92 .03 86	.92 .03 88	.90 .03 87
300	Weight, loss % Length, Exp. % RDM, %	.81 .03 87	.52 .03 84	.87 .03 89	.83 .03 89	1.30 .03 83	1.26 .03 84	1.19 .03 87	1.18 .03 86
	Durability Factor, %	87	84	89	89	83	84	87	86

Task #3
(Regional Testing/Hardened Air/ Freeze-Thaw)
MnDOT CONCRETE DELIVERY TIME STUDY
Plant #2: Duluth Ready Mix/Ready Mix Concrete, Inc. - August 26, 2010
Mix Proportions (SSD)

Batch #7- 3A32	**Mix Design**	**Adjusted Weights**
Cement, pcy	484	474
Fly Ash, pcy	85 (15%)	83 (15%)
3/4" Gravel, pcy	1,841	1,801
Concrete Sand, pcy	1,250	1,224
Water, pcy	258	253
Water Cementitious Ratio	.45	.45

Batch #8- 3Y43	**Mix Design**	**Adjusted Weights**
Cement, pcy	550	541
Fly Ash, pcy	97 (15%)	95 (15%)
3/4" Gravel, pcy	1,800	1,770
Concrete Sand, pcy	1,206	1,186
Water, pcy	284	279
Water Cementitious Ratio	.44	.44

Plastic Testing Results

Ambient Temperature, 67° F, Overcast

Table C6. Batch #7-3A32

Time	Slump, in.	Air, %	Unit Weight, lb/ft^3	Temperature, F
Initial	8.0	9.0	142.0	73
30 Minutes	7.5	8.5	140.0	74
60 Minutes	6.75	8.2	141.6	73
90 Minutes	6.0	7.9	141.6	75
120 Minutes	5.0	7.5	143.6	76

Table C7. Batch #8-3Y43

Time	Slump, in.	Air, %	Unit Weight, lb/ft^3	Temperature, F
Initial	7.0	8.3	143.4	75
30 Minutes	6.75	7.2	143.2	76
60 Minutes	6.25	7.5	141.6	78
90 Minutes	5.5	6.9	144.0	78
120 Minutes	4.75	6.0	146.4	78

Table C8. Hardened Air (%)

Batch No.	60 min	120 min
7	8.4	6.4
8	8.3	6.7
Average	**8.3**	**6.5**

Table C9. Compressive Strength Results, psi

Batch #	60 minutes*	90 Minutes*	120 Minutes*
7	3220	3670	3970
8	4510	4710	5230

* Average of 2 cylinders

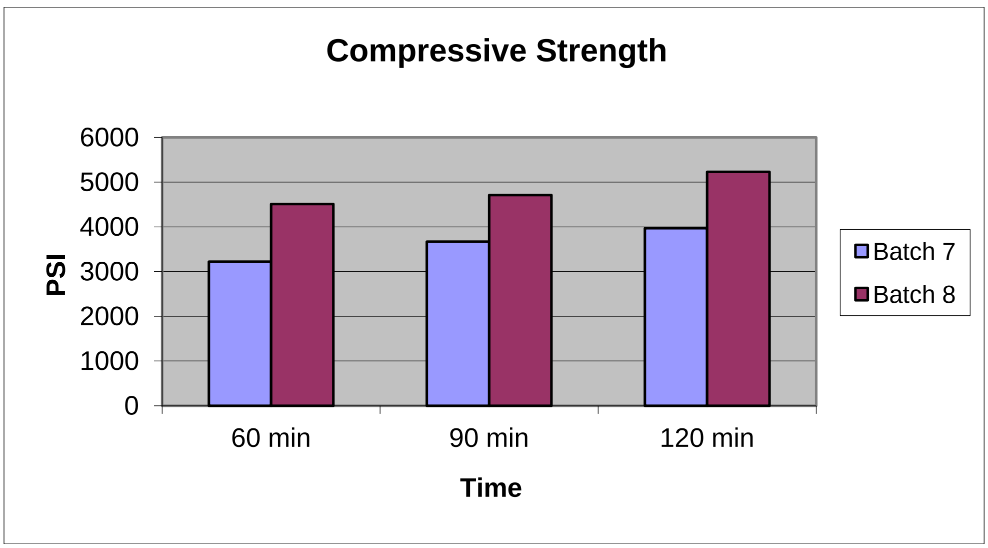


Figure C2. Compressive Strength

Table C10. Freeze-Thaw Results

Cycles		7A-60	7B-60	7A-120	7B-120	8A-60	8B-60	8A-120	8B-120
34	Weight, loss %	-.01	.03	-.01	.00	.03	.00	-.02	-.02
	Length, Exp. %	.00	.00	.00	.00	.00	.00	.00	.00
	RDM, %	99	100	100	99	100	99	99	100
68	Weight, loss %	.09	.10	.13	.11	.18	.15	.15	.16
	Length, Exp. %	.00	.00	.00	.00	.00	.00	.00	.00
	RDM, %	97	99	99	98	99	98	98	99
101	Weight, loss %	.16	.18	.20	.19	.24	.25	.26	.29
	Length, Exp. %	.01	.01	.01	.01	.01	.01	.01	.01
	RDM, %	96	97	97	96	98	97	97	97
136	Weight, loss %	.20	.21	.24	.23	.36	.38	.39	.40
	Length, Exp. %	.02	.02	.02	.02	.02	.02	.02	.02
	RDM, %	95	94	95	94	96	96	96	95
174	Weight, loss %	.24	.23	.26	.28	.44	.43	.43	.46
	Length, Exp. %	.02	.02	.02	.02	.02	.02	.02	.02
	RDM, %	94	93	94	92	94	95	95	94
208	Weight, loss %	.28	.26	.29	.31	.48	.46	.47	.50
	Length, Exp. %	.02	.02	.02	.02	.02	.02	.02	.02
	RDM, %	93	93	92	91	93	94	94	93
238	Weight, loss %	.35	.38	.39	.41	.51	.50	.52	.53
	Length, Exp. %	.03	.03	.03	.03	.03	.03	.03	.03
	RDM, %	92	92	91	90	93	94	92	92
273	Weight, loss %	.41	.42	.48	.50	.55	.52	.62	.63
	Length, Exp. %	.03	.03	.03	.03	.03	.03	.03	.03
	RDM, %	91	91	90	89	92	93	91	92
303	Weight, loss %	.45	.46	.53	.54	.61	.67	.68	.68
	Length, Exp. %	.03	.03	.03	.03	.03	.03	.03	.03
	RDM, %	90	90	89	88	92	93	90	91
	Durability Factor, %	90	90	89	88	92	93	90	91

Task #3
(Regional Testing/Hardened Air/ Freeze-Thaw)
MnDOT CONCRETE DELIVERY TIME STUDY
Plant #3: GCC Ready Mix St. James - September 9, 2010
Mix Proportions (SSD)

Batch #9- 3A32	**Mix Design**	**Adjusted Weights**
Cement, pcy	448	442
Fly Ash, pcy	112 (20%)	111 (20%)
3/4" Gravel, pcy	1,780	1,757
Concrete Sand, pcy	1,280	1,264
Water, pcy	250	247
Water Cementitious Ratio	.45	.45

Batch #10- 3Y43	**Mix Design**	**Adjusted Weights**
Cement, pcy	512	515
Fly Ash, pcy	128 (20%)	129 (20%)
3/4" Gravel, pcy	1,755	1,764
Concrete Sand, pcy	1,130	1,135
Water, pcy	288	289
Water Cementitious Ratio	.45	.45

Plastic Testing Results

Ambient Temperature, 60° F, Rainy

Table C11. Batch #9-3A32

Time	Slump, in.	Air, %	Unit Weight, lb/ft^3	Temperature, F
Initial	7.0	10.0	141.5	69
30 Minutes	6.75	9.2	142.1	68
60 Minutes	7.25	7.5	142.6	66
90 Minutes	5.25	6.6	143.2	65
120 Minutes	4.75	6.2	143.1	64

Table C12. Batch #10-3Y43

Time	Slump, in.	Air, %	Unit Weight, lb/ft^3	Temperature, F
Initial	9	8.2	141.9	68
30 Minutes	8.5	7.6	142.8	67
60 Minutes	8.75	6.9	142.7	66
90 Minutes	8.25	5.9	143.3	65
120 Minutes	7.5	4.9	143.2	64

Table C13. Hardened Air (%)

Batch No.	60 min	120 min
9	6.8	5.5
10	3.8	3.6
Average	**5.3**	**4.6**

Table C14. Compressive Strength Results, psi

Batch #	60 minutes*	90 Minutes*	120 Minutes*
9	4730	5060	5450
10	4610	4910	5380

*Average of two samples

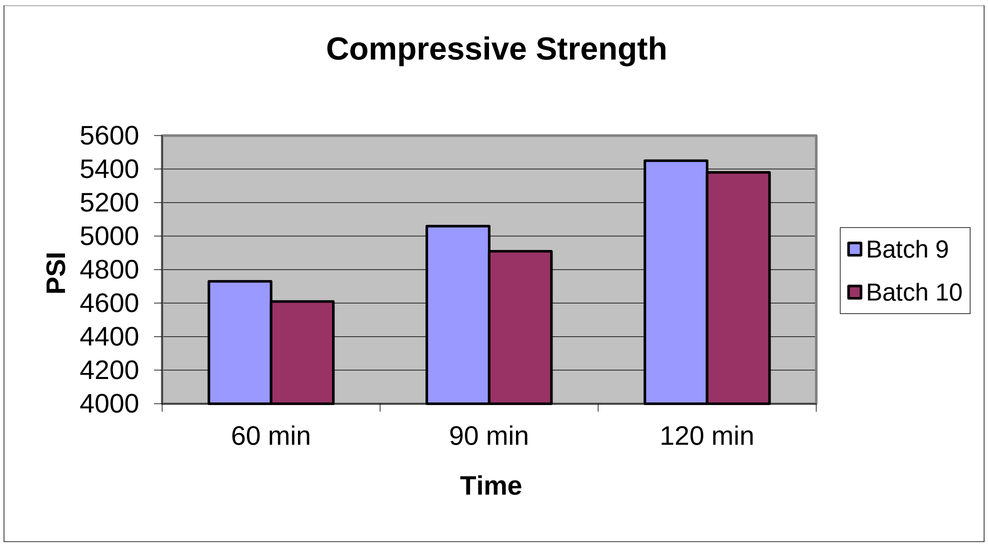


Figure C3. Compressive Strength

Table C15. Freeze-Thaw Results

Cycles		9A-60	9B-60	9A-120	9B-120	10A-60	10B-60	10A-120	10B-120
32	Weight, loss %	-.02	-.03	-.01	-.01	.09	.04	.01	.04
	Length, Exp. %	.00	.00	.00	.00	.00	.00	.00	.00
	RDM, %	100	100	100	100	97	96	98	98
68	Weight, loss %	.12	.09	.13	.10	.18	.08	.09	.10
	Length, Exp. %	.00	.00	.00	.00	.00	.00	.00	.00
	RDM, %	99	99	99	98	93	90	94	96
100	Weight, loss %	.17	.16	.20	.18	.25	.18	.15	.19
	Length, Exp. %	.01	.01	.01	.01	.01	.01	.01	.01
	RDM, %	98	97	97	97	95	95	94	95
132	Weight, loss %	.25	.24	.33	.31	.33	.25	.22	.24
	Length, Exp. %	.01	.01	.01	.01	.01	.01	.01	.01
	RDM, %	97	97	97	97	94	94	94	94
171	Weight, loss %	.32	.34	.38	.39	.41	.30	.28	.30
	Length, Exp. %	.02	.02	.02	.02	.02	.02	.02	.02
	RDM, %	97	97	96	96	93	92	94	92
208	Weight, loss %	.44	.44	.49	.50	.54	.48	.39	.42
	Length, Exp. %	.02	.02	.02	.02	.02	.02	.02	.02
	RDM, %	96	96	96	96	93	92	94	93
240	Weight, loss %	.51	.53	.57	.59	.62	.54	.47	.51
	Length, Exp. %	.02	.02	.02	.02	.02	.02	.02	.02
	RDM, %	95	95	95	94	93	92	94	93
271	Weight, loss %	.58	.59	.64	.66	.71	.60	.59	.63
	Length, Exp. %	.02	.02	.02	.02	.02	.02	.02	.02
	RDM, %	94	94	93	93	93	92	94	93
300	Weight, loss %	.64	.65	.71	.73	.87	.66	.63	.76
	Length, Exp. %	.03	.03	.03	.03	.03	.03	.03	.03
	RDM, %	93	93	92	92	92	92	94	92
	Durability Factor, %	93	93	92	92	92	92	94	92

Task #3
(Regional Testing/Hardened Air/ Freeze-Thaw)
MnDOT CONCRETE DELIVERY TIME STUDY
Plant #4: Knife River Baxter Plant - September 15, 2010
Mix Proportions (SSD)

Batch #11- 3A32	Mix Design	Adjusted Weights
Cement, pcy	449	454
Fly Ash, pcy	88 (16%)	89 (16%)
3/4" Gravel, pcy	1,882	1,903
Concrete Sand, pcy	1,279	1,294
Water, pcy	242	245
Water Cementitious Ratio	.45	.45

Batch #12- 3Y43	Mix Design	Adjusted Weights
Cement, pcy	530	532
Fly Ash, pcy	132 (20%)	133 (20%)
3/4" Gravel, pcy	1,796	1,804
Concrete Sand, pcy	1,160	1,165
Water, pcy	296	297
Water Cementitious Ratio	.45	.45

Plastic Testing Results

Ambient Temperature, 50° f, Overcast

Table C16. Batch #11-3A32

Time	Slump, in.	Air, %	Unit Weight, lb/ft^3	Temperature, F
Initial	3.75	6.2	147.6	68
30 Minutes	3.0	4.7	151.2	68
60 Minutes	1.75	3.8	150.4	72
90 Minutes	1.0	3.5	152	72
120 Minutes	0.75	3.2	152.4	75

Table C17. Batch #12-3Y43

Time	Slump, in.	Air, %	Unit Weight, lb/ft^3	Temperature, F
Initial	9	6.5	145.6	69
30 Minutes	9	4.9	149.2	69
60 Minutes	9	3.7	148.8	68
90 Minutes	9	2.6	151.2	69
120 Minutes	8.75	5.2	148.4	70

Table C18. Hardened Air (%)

Batch No.	60 min	120 min
11	3.0	2.5
12	5.4	2.4
Average	4.2	2.5

Table C19. Compressive Strength Results, psi

Batch #	60 minutes*	90 Minutes*	120 Minutes*
11	7810	6970	7240
12	6630	6450	6370

*Average of two samples

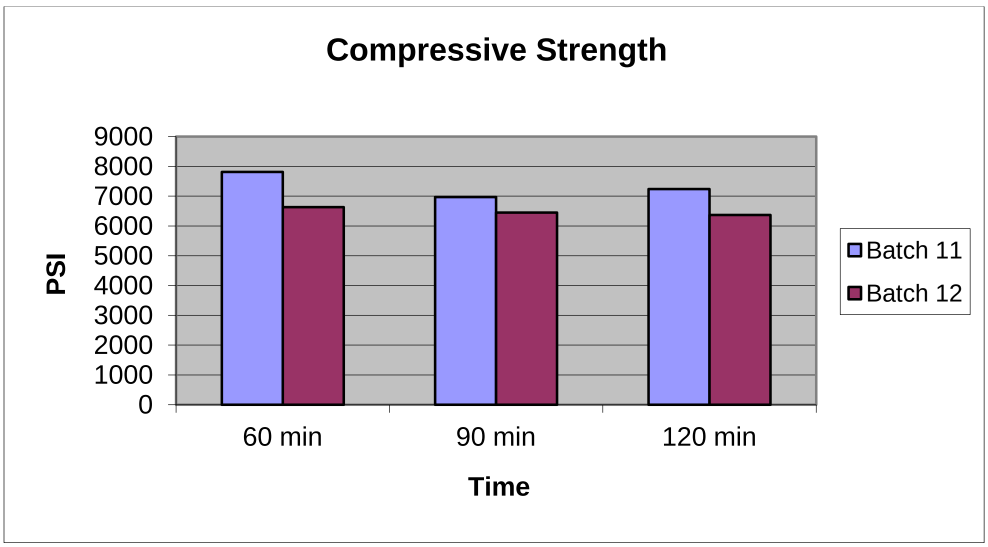


Figure C4. Compressive Strength

Table C20. Freeze-Thaw Results

Cycles		11A-60	11B-60	11A-120	11B-120	12A-60	12B-60	12A-120	12B-120
31	Weight, loss % Length, Exp. % RDM, %	.03 .00 100	.05 .00 99	.06 .00 100	.07 .00 100	.09 .00 100	.03 .00 99	.06 .00 100	.04 .00 99
67	Weight, loss % Length, Exp. % RDM, %	.06 .00 100	.10 .00 99	.12 .00 99	.12 .00 98	.17 .00 98	.08 .00 98	.13 .00 99	.19 .00 98
98	Weight, loss % Length, Exp. % RDM, %	.12 .00 98	.13 .00 98	.14 .00 97	.16 .00 96	.25 .00 95	.12 .00 95	.18 .00 97	.23 .00 96
128	Weight, loss % Length, Exp. % RDM, %	.18 .01 98	.14 .01 97	.17 .01 95	.18 .01 94	.35 .01 93	.15 .01 93	.22 .01 95	.28 .01 95
168	Weight, loss % Length, Exp. % RDM, %	.24 .01 97	.15 .01 96	.24 .01 93	.27 .01 93	.44 .01 91	.35 .01 90	.39 .01 94	.42 .01 93
205	Weight, loss % Length, Exp. % RDM, %	.31 .02 95	.24 .02 95	.36 .02 91	.37 .02 90	.51 .02 90	.42 .02 90	.44 .02 93	.49 .02 92
236	Weight, loss % Length, Exp. % RDM, %	.38 .02 94	.31 .02 93	.41 .02 90	.43 .02 89	.62 .02 89	.56 .02 89	.59 .02 92	.66 .02 91
268	Weight, loss % Length, Exp. % RDM, %	.42 .02 91	.36 .02 91	.52 .02 89	.54 .02 88	.72 .02 89	.72 .02 89	.92 .02 91	.95 .02 90
300	Weight, loss % Length, Exp. % RDM, %	.56 .03 89	.45 .03 89	.76 .03 86	.73 .03 85	.91 .03 86	.91 .03 87	1.29 .03 89	1.25 .03 88
	Durability Factor, %	89	89	86	85	86	87	89	88

Task #3
(Regional Testing/Hardened Air/ Freeze-Thaw)
MnDOT CONCRETE DELIVERY TIME STUDY
Plant #5: Cemstone Childs Road Plant - September 23, 2010
Mix Proportions (SSD)

Batch #13- 3A32	Mix Design	Adjusted Weights
Cement, pcy	432	433
Fly Ash, pcy	108 (20%)	109 (20%)
3/4" Gravel, pcy	682	685
1/2" Gravel, pcy	1,162	1,167
Concrete Sand, pcy	1,258	1,264
Water, pcy	244	245
Water Cementitious Ratio	.45	.45

Batch #14- 3Y43	Mix Design	Adjusted Weights
Cement, pcy	470	469
Fly Ash, pcy	117 (20%)	117 (20%)
3/4" Gravel, pcy	656	655
1/2" Gravel, pcy	1,117	1,115
Concrete Sand, pcy	1,210	1,208
Water, pcy	265	265
Water Cementitious Ratio	.45	.45

Plastic Testing Results

Ambient Temperature, 64° F, Steady rain

Table C21. Batch #13-3A32

Time	Slump, in.	Air, %	Unit Weight, lb/ft^3	Temperature, F
Initial	5.5	8.2	144.4	69
30 Minutes	4.75	7.5	147.2	70
60 Minutes	4.0	5.9	148	68
90 Minutes	3.0	5.7	147.6	72
120 Minutes	1.5	3.0	151.6	74

Table C22. Batch #14-3Y43

Time	Slump, in.	Air, %	Unit Weight, lb/ft^3	Temperature, F
Initial	6.0	9.5	141.8	70
30 Minutes	5.75	8.9	142	70
60 Minutes	4.75	7.2	144	72
90 Minutes	3.0	6.8	144	73
120 Minutes	1.25	5.5	145.2	75

Table C23. Hardened Air (%)

Batch No.	60 min	120 min
13	5.8	2.8
14	5.2	5.0
Average	**5.5**	**3.9**

Table C24. Compressive Strength Results, psi

Batch #	60 minutes*	90 Minutes*	120 Minutes*
13	4380	5030	5500
14	4450	4310	4780

*Average of two cylinders

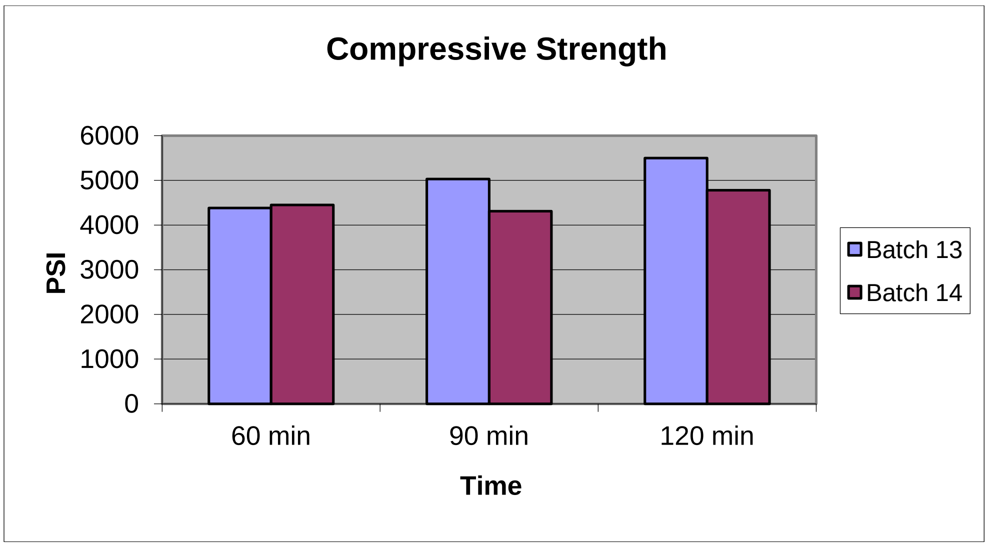


Figure C5. Compressive Strength

Table C25. Freeze-Thaw Results

Cycles		13A-60	13B-60	13A-120	13B-120	14A-60	14B-60	14A-120	14B-120
32	Weight, loss %	-.02	-.03	-.01	.02	-.02	.00	.05	-.02
	Length, Exp. %	.00	.00	.00	.00	.00	.00	.00	.00
	RDM, %	100	100	100	100	100	100	99	100
68	Weight, loss %	.14	.07	.11	.15	.16	.15	.14	.10
	Length, Exp. %	.00	.01	.00	.00	.00	.00	.00	.00
	RDM, %	99	99	99	98	99	98	98	99
100	Weight, loss %	.24	.14	.20	.23	.38	.22	.24	.16
	Length, Exp. %	.01	.01	.01	.01	.01	.01	.01	.01
	RDM, %	97	97	98	96	98	96	97	97
132	Weight, loss %	.33	.26	.29	.31	.51	.38	.45	.29
	Length, Exp. %	.01	.01	.01	.01	.01	.01	.01	.01
	RDM, %	96	96	97	95	97	95	96	96
171	Weight, loss %	.54	.38	.45	.48	.65	.51	.60	.34
	Length, Exp. %	.01	.01	.01	.01	.01	.01	.01	.01
	RDM, %	95	96	95	94	96	94	95	95
208	Weight, loss %	.74	.46	.54	.59	.79	.70	.72	.49
	Length, Exp. %	.02	.02	.02	.02	.02	.02	.02	.02
	RDM, %	93	94	93	92	94	93	94	93
240	Weight, loss %	.87	.51	.63	.71	.85	.79	.80	.63
	Length, Exp. %	.02	.02	.02	.02	.02	.02	.02	.02
	RDM, %	91	91	91	90	91	91	90	90
271	Weight, loss %	.96	.58	.74	.82	.90	.87	.85	.88
	Length, Exp. %	.02	.02	.02	.02	.02	.02	.02	.02
	RDM, %	89	90	89	88	87	88	87	87
300	Weight, loss %	1.05	.69	.85	1.03	1.13	1.10	1.08	1.11
	Length, Exp. %	.03	.03	.03	.03	.03	.03	.03	.03
	RDM, %	87	88	87	88	86	87	86	86
	Durability Factor, %	87	88	87	88	86	87	86	86

Task #3
(Regional Testing/Hardened Air/ Freeze-Thaw)
MnDOT CONCRETE DELIVERY TIME STUDY
Plant #6: AVR Burnsville - September 30, 2010
Mix Proportions (SSD)

Batch #15- 3A32	Mix Design	Adjusted Weights
Cement, pcy	470	473
Fly Ash, pcy	117 (20%)	118 (20%)
3/4" Gravel, pcy	1,783	1,793
Concrete Sand, pcy	1,330	1,337
Water, pcy	264	265
Water Cementitious Ratio	.45	.45

Batch #16- 3Y43	Mix Design	Adjusted Weights
Cement, pcy	517	510
Fly Ash, pcy	129 (20%)	127 (20%)
3/4" Gravel, pcy	1,746	1,724
Concrete Sand, pcy	1,310	1,293
Water, pcy	291	287
Water Cementitious Ratio	.45	.45

Plastic Testing Results

Ambient Temperature, 66°F, Sunny

Table C26. Batch #15-3A32

Time	Slump, in.	Air, %	Unit Weight, lb/ft^3	Temperature, F
Initial	4.25	4.6	147.6	75
30 Minutes	3.5	4.6	147.6	76
60 Minutes	1.25	3.8	149.2	80
90 Minutes	1.0	3.2	149.6	83
120 Minutes	0.5	3.2	150.8	85

Table C27. Batch #16-3Y43

Time	Slump, in.	Air, %	Unit Weight, lb/ft^3	Temperature, F
Initial	6.5	5.7	146	73
30 Minutes	5.25	4.5	148.8	75
60 Minutes	3.5	4.3	148.4	77
90 Minutes	2.0	3.8	148.8	80
120 Minutes	1.25	3.6	148.8	81

Table C28. Hardened Air (%)

Batch No.	Initial	120 min
15	4.2	4.4
16	3.0	3.1
Average	3.6	3.8

Table C29. Compressive Strength Results, psi

Batch #	60 minutes*	90 Minutes*	120 Minutes*
15	7720	7320	7300
16	8080	7400	7710

*Average of two cylinders

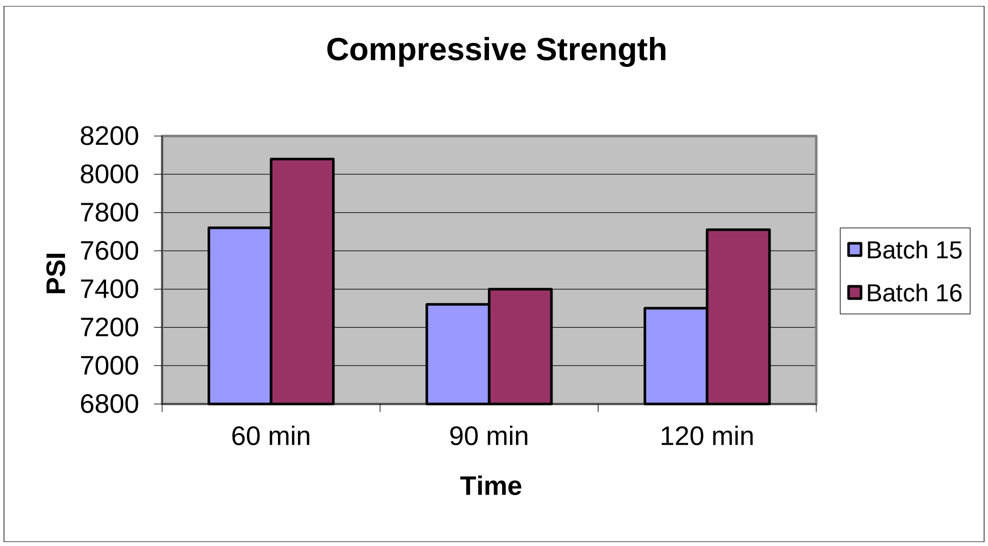


Figure C6. Compressive Strength

Table C30. Freeze-Thaw Results

Cycles		15A-60	15B-60	15A-120	15B-120	16A-60	16B-60	16A-120	16B-120
29	Weight, loss % Length, Exp. % RDM, %	-.02 .00 99	-.03 .00 100	-.01 .00 100	-.01 .00 99	-.02 .00 100	.00 .00 99	-.02 .00 99	-.02 .00 100
63	Weight, loss % Length, Exp. % RDM, %	.12 .00 98	.10 .00 99	.13 .00 99	.14 .00 98	.15 .00 99	.16 .00 97	.18 .00 97	.16 .00 98
97	Weight, loss % Length, Exp. % RDM, %	.24 .01 96	.26 .01 96	.20 .01 96	.22 .01 95	.18 .01 95	.20 .01 96	.23 .01 95	.22 .01 96
129	Weight, loss % Length, Exp. % RDM, %	.36 .01 95	.38 .01 95	.32 .01 96	.39 .01 94	.32 .01 94	.36 .01 95	.48 .01 94	.41 .01 95
168	Weight, loss % Length, Exp. % RDM, %	.43 .01 94	.48 .01 95	.40 .01 94	.46 .01 93	.44 .01 93	.48 .01 93	.62 .01 94	.55 .01 94
206	Weight, loss % Length, Exp. % RDM, %	.52 .02 94	.59 .02 94	.53 .02 93	.62 .02 92	.51 .02 92	.53 .02 92	.76 .02 93	.74 .02 93
241	Weight, loss % Length, Exp. % RDM, %	.68 .02 93	.73 .02 93	.71 .02 92	.76 .02 91	.65 .02 92	.68 .02 92	.84 .02 92	.81 .02 92
271	Weight, loss % Length, Exp. % RDM, %	.75 .02 92	.79 .02 92	.78 .02 91	.82 .02 90	.72 .02 91	.76 .02 91	.91 .02 91	.89 .02 91
300	Weight, loss % Length, Exp. % RDM, %	.87 .03 91	.92 .03 92	.90 .03 90	.95 .03 89	.81 .03 91	.83 .03 90	.98 .03 90	.94 .03 90
	Durability Factor, %	91	92	90	89	91	90	90	90

Task #3
(Regional Testing/Hardened Air/ Freeze-Thaw)
MnDOT CONCRETE DELIVERY TIME STUDY
Plant #7: Aggregate Industries- Minneapolis - October 7, 2010
Mix Proportions (SSD)

Batch #17- 3A32	Mix Design	Adjusted Weights
Cement, pcy	448	445
Fly Ash, pcy	112 (20%)	111 (20%)
3/4" Gravel, pcy	1,212	1,205
3/8" Gravel, pcy	664	660
Concrete Sand, pcy	1,234	1,227
Water, pcy	252	251
Water Cementitious Ratio	.45	.45

Batch #18- 3Y43	Mix Design	Adjusted Weights
Cement, pcy	512	512
Fly Ash, pcy	128 (20%)	128 (20%)
3/4" Gravel, pcy	1,171	1,172
3/8" Gravel, pcy	624	625
Concrete Sand, pcy	1,194	1,195
Water, pcy	288	288
Water Cementitious Ratio	.45	.45

Plastic Testing Results

Ambient Temperature, 70° F, Sunny

Table C31. Batch #17-3A32

Time	Slump, in.	Air, %	Unit Weight, lb/ft^3	Temperature, F
Initial	5.5	9.9	144.4	62
30 Minutes	9.0	8.4	146.0	62
60 Minutes	4.5	8.0	156.4	62
90 Minutes	4.0	7.3	147.6	62
120 Minutes	3.25	6.7	152.4	62

Table C32. Batch #18-3Y43

Time	Slump, in.	Air, %	Unit Weight, lb/ft^3	Temperature, F
Initial	6.0	9.0	145.2	66
30 Minutes	4.0	8.5	148.4	68
60 Minutes	2.5	6.7	149.2	70
90 Minutes	1.5	5.0	150.8	71
120 Minutes	1.0	4.0	152.0	74

Table C33. Hardened Air (%)

Batch No.	60 min	120 min
17	6.2	4.6
18	5.2	3.9
Average	5.7	4.3

Table C34. Compressive Strength Results, psi

Batch #	60 minutes*	90 Minutes*	120 Minutes*
17	5320	5380	5410
18	6140	6630	7620

*Average of two cylinders

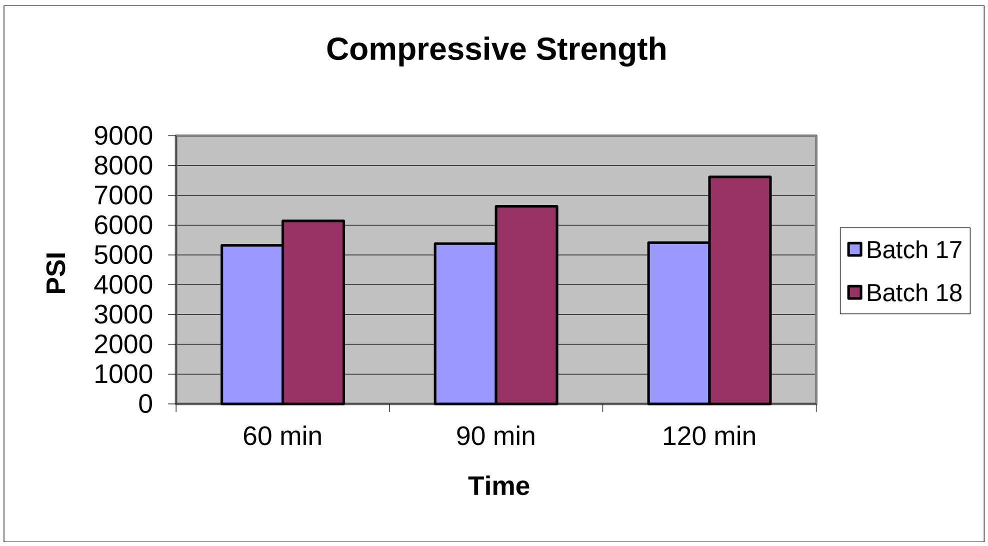


Figure C7. Compressive Strength

Table C35. Freeze-Thaw Results

Cycles		17A-60	17B-60	17A-120	17B-120	18A-60	18B-60	18A-120	18B-120
37	Weight, loss %	.00	.01	-.01	-.01	.02	.00	-.02	.01
	Length, Exp. %	.00	.00	.00	.00	.00	.00	.00	.00
	RDM, %	100	100	100	99	100	100	100	100
73	Weight, loss %	.09	.12	.15	.14	.09	.10	.10	.12
	Length, Exp. %	.00	.00	.00	.00	.00	.00	.00	.00
	RDM, %	99	98	99	99	99	99	99	99
105	Weight, loss %	.17	.19	.21	.26	.15	.17	.19	.21
	Length, Exp. %	.00	.00	.00	.00	.00	.00	.00	.00
	RDM, %	98	97	97	98	98	98	97	98
140	Weight, loss %	.29	.32	.37	.41	.26	.25	.29	.32
	Length, Exp. %	.00	.00	.00	.00	.00	.00	.00	.00
	RDM, %	97	96	95	96	97	97	96	96
173	Weight, loss %	.42	.45	.49	.51	.38	.35	.42	.46
	Length, Exp. %	.00	.00	.00	.00	.00	.00	.00	.00
	RDM, %	96	95	94	95	96	96	95	95
205	Weight, loss %	.54	.59	.62	.65	.46	.42	.51	.55
	Length, Exp. %	.01	.01	.01	.01	.01	.01	.01	.01
	RDM, %	95	94	93	94	95	95	94	93
242	Weight, loss %	.65	.71	.75	.77	.59	.55	.63	.68
	Length, Exp. %	.01	.01	.01	.01	.01	.01	.01	.01
	RDM, %	94	93	92	92	94	94	93	92
273	Weight, loss %	.71	.80	.86	.88	.64	.66	.76	.79
	Length, Exp. %	.02	.02	.02	.02	.01	.01	.01	.01
	RDM, %	92	91	91	90	93	92	91	90
303	Weight, loss %	.83	.89	.97	1.00	.78	.80	.88	.99
	Length, Exp. %	.02	.02	.03	.03	.02	.02	.03	.02
	RDM, %	90	89	88	88	91	90	89	88
	Durability Factor, %	90	89	88	88	91	90	89	88

APPENDIX D: HARDENED AIR CONTENTS

American Petrographic Services, Inc.

PROJECT:
TRUCK TRANSIT
AIR CONTENT STUDY

REPORTED TO:
MINNESOTA DEPARTMENT OF TRANSPORTATION
MAIL STOP 645
MAPLEWOOD, MN 55109

ATTN: MARIA MASTEN

APS JOB NO:10-06561

DATE: JUNE 17, 2010

Sample ID: Task 1 Batch 1 (Initial)

Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.

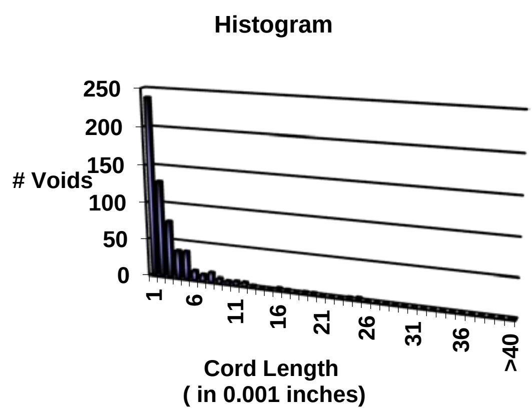
Sample Data:

Description: Hardened Concrete Cylinder

Dimensions: 102 mm (4") diameter x 203 mm (8") long

Test Data: ASTM:C457 Linear Traverse Method, APS SOP 00LAB003 and ACI 116R

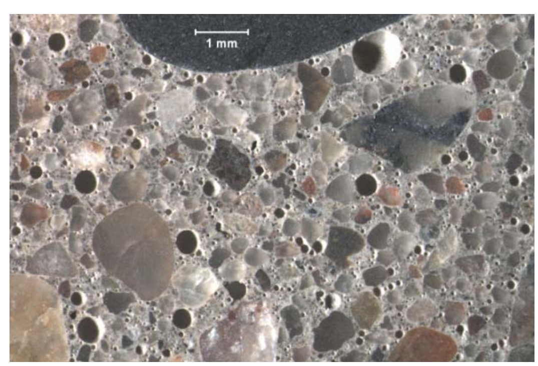
Air Void Content %	4.2
Entrained, % ≤ 0.040”	3.9
Entrapped, %> 0.040”	0.3
Air Voids/inch	11.63
Specific Surface, in2/in3	1120
Spacing Factor, inches	0.005
Paste Content, % estimated	26.0
Magnification	50x
Traverse Length, inches	51
Test Date	06/17/2010



The test sample will be retained for at least 30 days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. Test results relate only to the item tested.

Report Prepared By:

Scott Wolter, PG
President
MN License #30024



Magnification: 15x
Description: Overall hardened air content, 4.2% total

American Petrographic Services, Inc.

PROJECT:
TRUCK TRANSIT
AIR CONTENT STUDY

REPORTED TO:
MINNESOTA DEPARTMENT OF TRANSPORTATION
MAIL STOP 645
MAPLEWOOD, MN 55109

ATTN: MARIA MASTEN
DATE: JUNE 17, 2010

APS JOB NO:10-06561

Sample ID: Task 1 Batch 1 (120 min.)

Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.

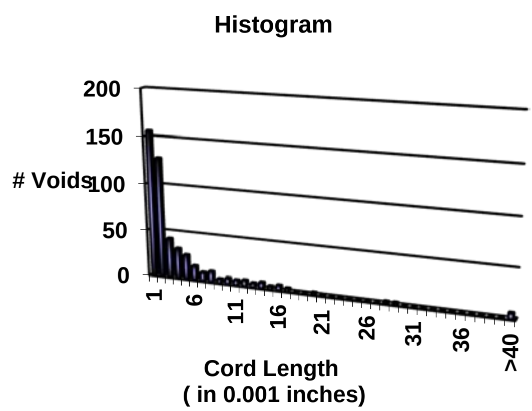
Sample Data:

Description: Hardened Concrete Cylinder

Dimensions: 102 mm (4") diameter x 176 mm (6-15/16") long

Test Data: ASTM:C457 Linear Traverse Method, APS SOP 00LAB003 and ACI 116R

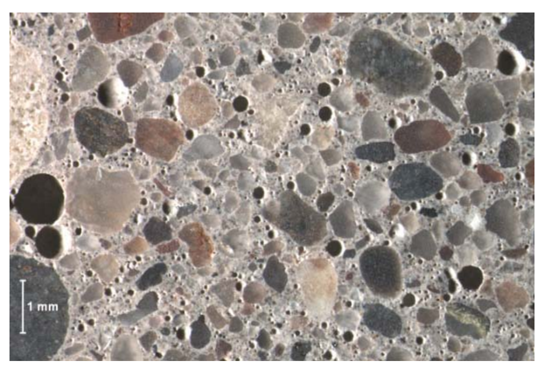
Air Void Content %	5.2
Entrained, % ≤ 0.040”	3.8
Entrapped, %> 0.040”	1.4
Air Voids/inch	9.43
Specific Surface, in2/in3	720
Spacing Factor, inches	0.006
Paste Content, % estimated	26.0
Magnification	50x
Traverse Length, inches	51
Test Date	06/17/2010



The test sample will be retained for at least 30 days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. Test results relate only to the item tested.

Report Prepared By:

Scott Wolter, PG
President
MN License #30024



Magnification: 15x
Description: Overall hardened air content, 5.2% total

American Petrographic Services, Inc.

PROJECT:
TRUCK TRANSIT
AIR CONTENT STUDY

REPORTED TO:
MINNESOTA DEPARTMENT OF TRANSPORTATION
MAIL STOP 645
MAPLEWOOD, MN 55109

ATTN: MARIA MASTEN
DATE: JUNE 18, 2010

APS JOB NO:10-06561

Sample ID: Task 1 Batch 3 (Initial)

Conformance: The sample contains an air void system which is generally consistent with current technology for freeze-thaw resistance.

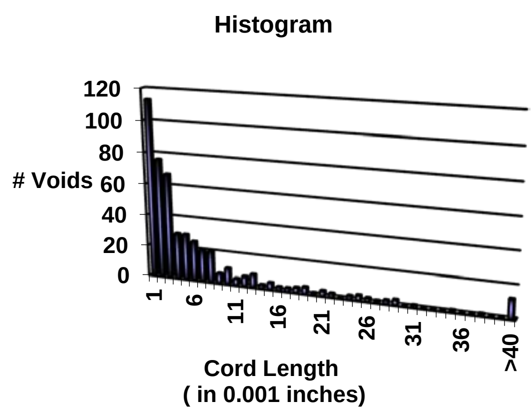
Sample Data:

Description: Hardened Concrete Cylinder

Dimensions: 102 mm (4") diameter x 203 mm (8") long

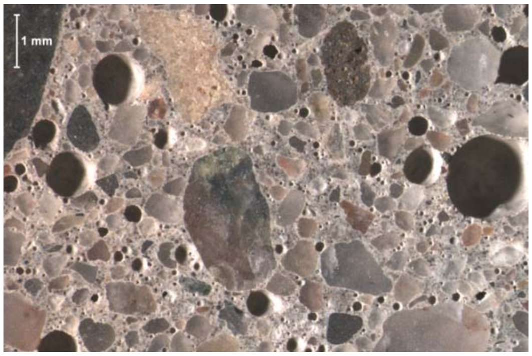
Test Data: ASTM:C457 Linear Traverse Method, APS SOP 00LAB003 and ACI 116R

Air Void Content %	6.1
Entrained, % ≤ 0.040”	4.4
Entrapped, %> 0.040”	1.7
Air Voids/inch	8.29
Specific Surface, in2/in3	540
Spacing Factor, inches	0.008
Paste Content, % estimated	26.0
Magnification	50x
Traverse Length, inches	56
Test Date	06/18/2010



The test sample will be retained for at least 30 days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. Test results relate only to the item tested.
Report Prepared By:

Scott Wolter, PG
President
MN License #30024



Magnification: 15x
Description: Overall hardened air content, 6.1% total

American Petrographic Services, Inc.

PROJECT:	**REPORTED TO:**
TRUCK TRANSIT	MINNESOTA DEPARTMENT OF TRANSPORTATION
AIR CONTENT STUDY	MAIL STOP 645
	MAPLEWOOD, MN 55109
	ATTN: MARIA MASTEN
APS JOB NO:10-06561	**DATE:** JUNE 22, 2010

Sample ID: Task 1 Batch 3 (120 min.)

Conformance: The sample contains an air void system which is generally consistent with current technology for freeze-thaw resistance.

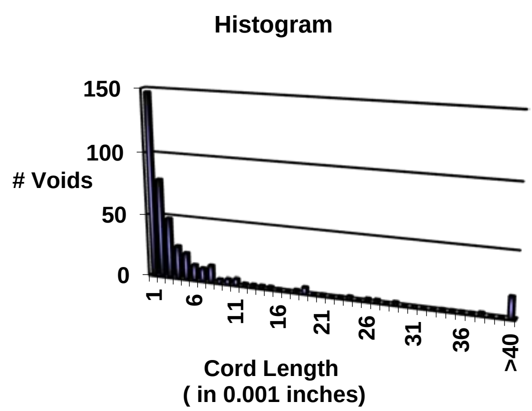
Sample Data:

Description: Hardened Concrete Cylinder

Dimensions: 102 mm (4") diameter x 203 mm (8") long

Test Data: ASTM:C457 Linear Traverse Method, APS SOP 00LAB003 and ACI 116R

Air Void Content %	5.8
Entrained, % ≤ 0.040”	3.4
Entrapped, %> 0.040”	2.4
Air Voids/inch	8.18
Specific Surface, in2/in3	560
Spacing Factor, inches	0.008
Paste Content, % estimated	26.0
Magnification	50x
Traverse Length, inches	51
Test Date	06/22/2010



The test sample will be retained for at least 30 days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. Test results relate only to the item tested.

Report Prepared By:

Scott Wolter, PG
President
MN License #30024

Magnification: 15x
Description: Overall hardened air content, 5.8% total

PROJECT:
TRUCK TRANSIT
AIR CONTENT STUDY

REPORTED TO:
MINNESOTA DEPARTMENT OF TRANSPORTATION
MAIL STOP 645
MAPLEWOOD, MN 55109

APS JOB NO:10-06561

ATTN: MARIA MASTEN
DATE: JUNE 22, 2010

Sample ID: Task 1 Batch 9 (Initial)

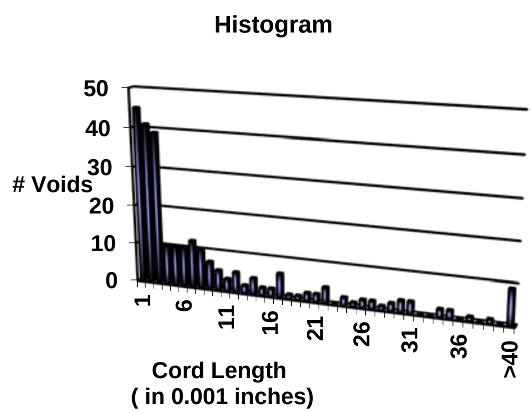
Conformance: The sample contains an air void system which is not consistent with current technology for freeze-thaw resistance.

Sample Data:

Description: Hardened Concrete Cylinder
Dimensions: 102 mm (4") diameter x 203 mm (8") long

Test Data: ASTM:C457 Linear Traverse Method, APS SOP 00LAB003 and ACI 116R

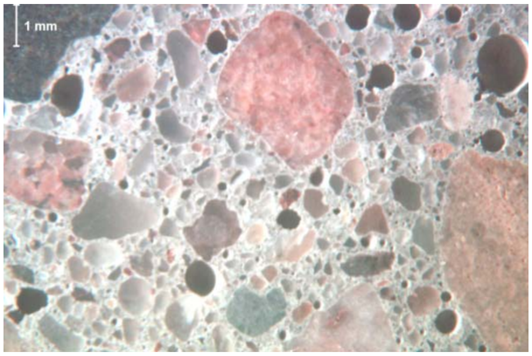
Air Void Content %	4.8
Entrained, % < 0.040”	3.7
Entrapped, %> 0.040”	1.1
Air Voids/inch	4.98
Specific Surface, in2/in3	410
Spacing Factor, inches	0.012
Paste Content, % estimated	26.0
Magnification	50x
Traverse Length, inches	51
Test Date	06/22/2010



The test sample will be retained for at least 30 days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. Test results relate only to the item tested.

Report Prepared By:

Scott Wolter, PG
President
MN License #30024



Magnification: 15x
Description: Overall hardened air content, 4.8% total

American Petrographic Services, Inc.

PROJECT:
TRUCK TRANSIT
AIR CONTENT STUDY

REPORTED TO:
MINNESOTA DEPARTMENT OF TRANSPORTATION
MAIL STOP 645
MAPLEWOOD, MN 55109

ATTN: MARIA MASTEN

APS JOB NO: 10-06561

DATE: JUNE 22, 2010

Sample ID: Task 1 Batch 9 (120 min.)

Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.

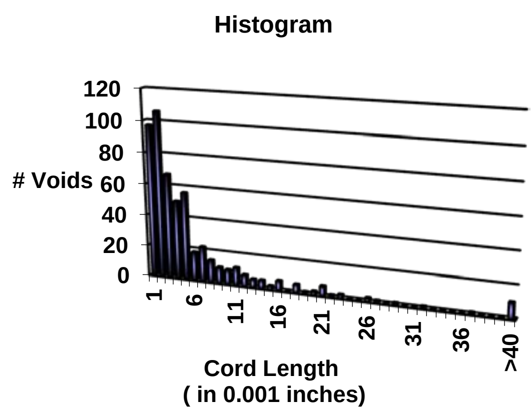
Sample Data:

Description: Hardened Concrete Cylinder

Dimensions: 102 mm (4") diameter x 203 mm (8") long

Test Data: ASTM:C457 Linear Traverse Method, APS SOP 00LAB003 and ACI 116R

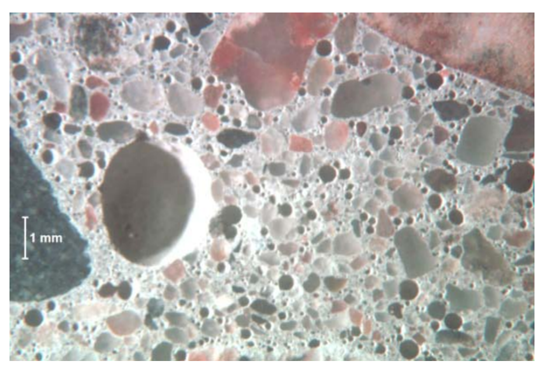
Air Void Content %	6.1
Entrained, % ≤ 0.040”	5.0
Entrapped, %> 0.040”	1.1
Air Voids/inch	10.16
Specific Surface, in2/in3	660
Spacing Factor, inches	0.007
Paste Content, % estimated	26.0
Magnification	50x
Traverse Length, inches	51
Test Date	06/22/2010



The test sample will be retained for at least 30 days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. Test results relate only to the item tested.

Report Prepared By:

Scott Wolter, PG
President
MN License #30024



Magnification: 15x
Description: Overall hardened air content, 6.1% total

American Petrographic Services, Inc.

PROJECT:	**REPORTED TO:**
TRUCK TRANSIT	MINNESOTA DEPARTMENT OF TRANSPORTATION
AIR CONTENT STUDY	MAIL STOP 645
	MAPLEWOOD, MN 55109
	ATTN: MARIA MASTEN
APS JOB NO:10-06561	**DATE:** JUNE 23, 2010

Sample ID: Task 1 Batch 12 (Initial)

Conformance: The sample contains an air void system which is not consistent with current technology for freeze-thaw resistance.

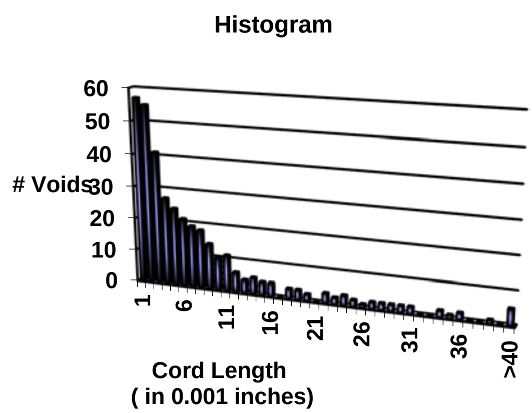
Sample Data:

Description: Hardened Concrete Cylinder

Dimensions: 102 mm (4") diameter x 203 mm (8") long

Test Data: ASTM:C457 Linear Traverse Method, APS SOP 00LAB003 and ACI 116R

Air Void Content %	5.5
Entrained, % ≤ 0.040”	4.9
Entrapped, %> 0.040”	0.6
Air Voids/inch	7.06
Specific Surface, in2/in3	520
Spacing Factor, inches	0.009
Paste Content, % estimated	26.0
Magnification	50x
Traverse Length, inches	51
Test Date	06/23/2010

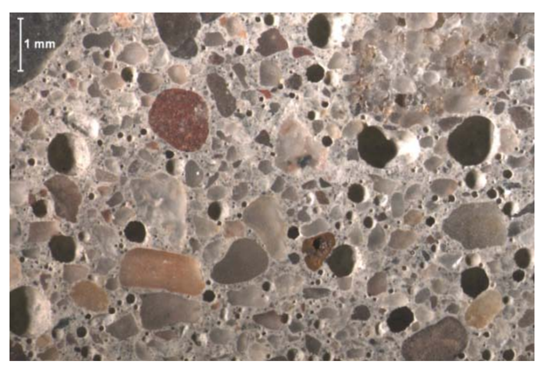


The test sample will be retained for at least 30 days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. Test results relate only to the item tested.

Report Prepared By:

Scott Wolter

Scott Wolter, PG
President
MN License #30024



Magnification: 15x
Description: Overall hardened air content, 5.6% total

American Petrographic Services, Inc.

PROJECT:
TRUCK TRANSIT
AIR CONTENT STUDY

REPORTED TO:
MINNESOTA DEPARTMENT OF TRANSPORTATION
MAIL STOP 645
MAPLEWOOD, MN 55109

ATTN: MARIA MASTEN

APS JOB NO:10-06561

DATE: JUNE 23, 2010

Sample ID: Task 1 Batch 12 (120 min.)

Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.

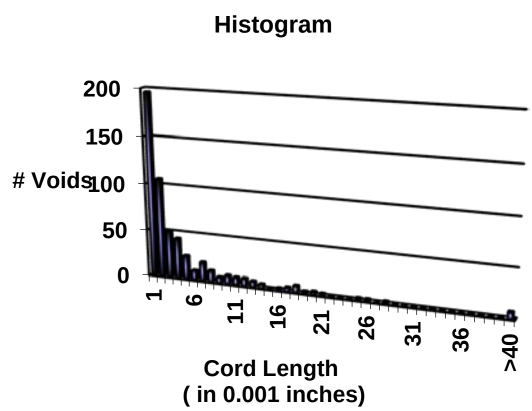
Sample Data:

Description: Hardened Concrete Cylinder

Dimensions: 102 mm (4") diameter x 203 mm (8") long

Test Data: ASTM:C457 Linear Traverse Method, APS SOP 00LAB003 and ACI 116R

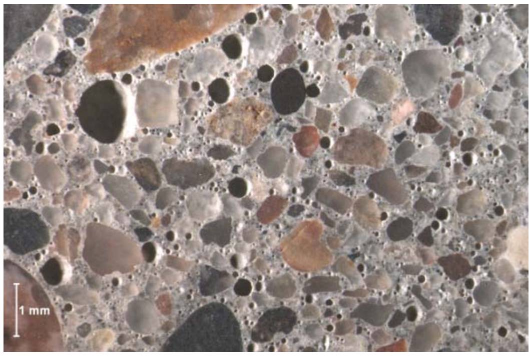
Air Void Content %	5.1
Entrained, % ≤ 0.040”	4.6
Entrapped, %> 0.040”	0.5
Air Voids/inch	10.59
Specific Surface, in2/in3	820
Spacing Factor, inches	0.006
Paste Content, % estimated	26.0
Magnification	50x
Traverse Length, inches	51
Test Date	06/23/2010



The test sample will be retained for at least 30 days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. Test results relate only to the item tested.

Report Prepared By:

Scott Wolter, PG
President
MN License #30024



Magnification: 15x
Description: Overall hardened air content, 5.1% total

American Petrographic Services, Inc.

PROJECT:
TRUCK TRANSIT
AIR CONTENT STUDY

REPORTED TO:
MINNESOTA DEPARTMENT OF TRANSPORTATION
MAIL STOP 645
MAPLEWOOD, MN 55109

ATTN: MARIA MASTEN

APS JOB NO:10-06561

DATE: JUNE 28, 2010

Sample ID: Task 1 Batch 16 (Initial)

Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.

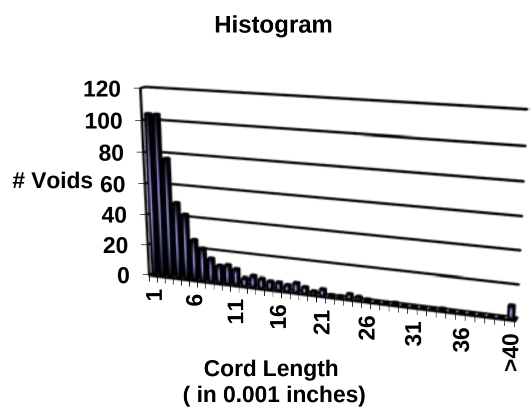
Sample Data:

Description: Hardened Concrete Cylinder

Dimensions: 102 mm (4") diameter x 203 mm (8") long

Test Data: ASTM:C457 Linear Traverse Method, APS SOP 00LAB003 and ACI 116R

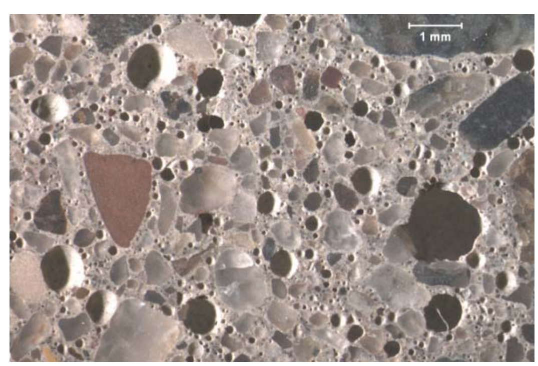
Air Void Content %	6.2
Entrained, % ≤ 0.040”	5.3
Entrapped, %> 0.040”	0.9
Air Voids/inch	10.53
Specific Surface, in2/in3	680
Spacing Factor, inches	0.006
Paste Content, % estimated	26.0
Magnification	50x
Traverse Length, inches	51
Test Date	06/24/2010



The test sample will be retained for at least 30 days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. Test results relate only to the item tested.

Report Prepared By:

Scott Wolter, PG
President
MN License #30024



Magnification: 15x
Description: Overall hardened air content, 6.2% total

American Petrographic Services, Inc.

PROJECT:
TRUCK TRANSIT
AIR CONTENT STUDY

REPORTED TO:
MINNESOTA DEPARTMENT OF TRANSPORTATION
MAIL STOP 645
MAPLEWOOD, MN 55109

ATTN: MARIA MASTEN

APS JOB NO:10-06561

DATE: JUNE 28, 2010

Sample ID: Task 1 Batch 16 (120 min.)

Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.

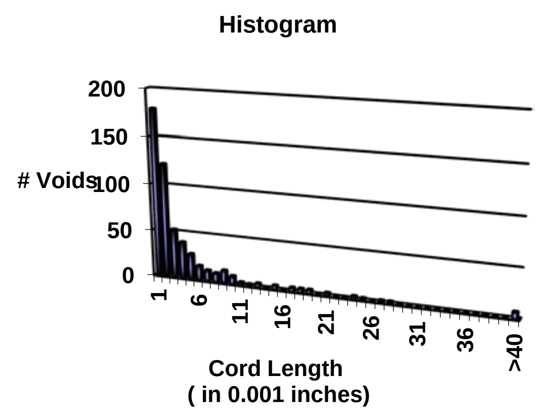
Sample Data:

Description: Hardened Concrete Cylinder

Dimensions: 102 mm (4") diameter x 203 mm (8") long

Test Data: ASTM:C457 Linear Traverse Method, APS SOP 00LAB003 and ACI 116R

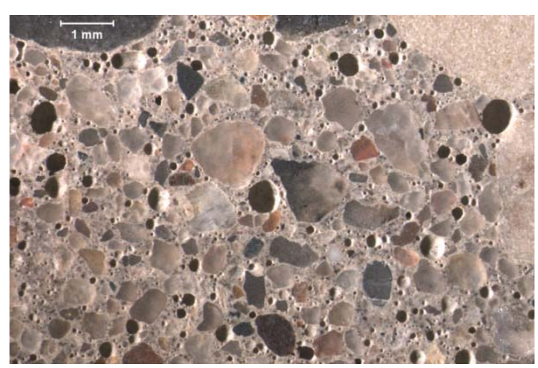
Air Void Content %	5.0
Entrained, % ≤ 0.040”	4.2
Entrapped, %> 0.040”	0.8
Air Voids/inch	10.29
Specific Surface, in2/in3	820
Spacing Factor, inches	0.006
Paste Content, % estimated	26.0
Magnification	50x
Traverse Length, inches	51
Test Date	06/24/2010



The test sample will be retained for at least 30 days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. Test results relate only to the item tested.

Report Prepared By:

Scott Wolter, PG
President
MN License #30024



Magnification: 15x
Description: Overall hardened air content, 5.0% total

American Petrographic Services, Inc.

PROJECT:
TRUCK TRANSIT
AIR CONTENT STUDY

REPORTED TO:
MINNESOTA DEPARTMENT OF TRANSPORTATION
MAIL STOP 645
MAPLEWOOD, MN 55109

ATTN: MARIA MASTEN
DATE: JUNE 28, 2010

APS JOB NO:10-06561

Sample ID: Task 1 Batch 23 (Initial)

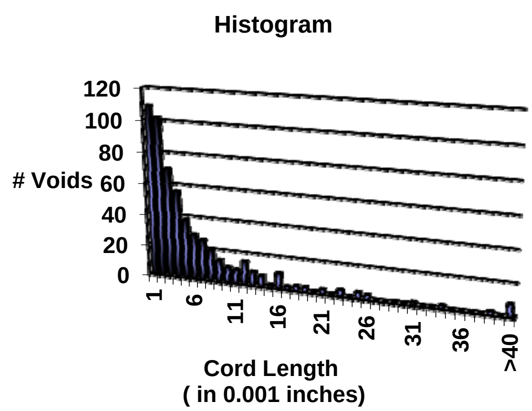
Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.

Sample Data:

Description: Hardened Concrete Cylinder
Dimensions: 102 mm (4") diameter x 203 mm (8") long

Test Data: ASTM:C457 Linear Traverse Method, APS SOP 00LAB003 and ACI 116R

Air Void Content %	7.4
Entrained, % ≤ 0.040”	6.2
Entrapped, %> 0.040”	1.2
Air Voids/inch	11.12
Specific Surface, in2/in3	600
Spacing Factor, inches	0.007
Paste Content, % estimated	26.0
Magnification	50x
Traverse Length, inches	51
Test Date	06/25/2010



The test sample will be retained for at least 30 days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. Test results relate only to the item tested.

Report Prepared By:

Scott Wolter, PG
President
MN License #30024

Magnification: 15x
Description: Overall hardened air content, 7.4% total

PROJECT:
TRUCK TRANSIT
AIR CONTENT STUDY

REPORTED TO:
MINNESOTA DEPARTMENT OF TRANSPORTATION
MAIL STOP 645
MAPLEWOOD, MN 55109

ATTN: MARIA MASTEN

APS JOB NO:10-06561

DATE: JUNE 28, 2010

Sample ID: Task 1 Batch 23 (120 min.)

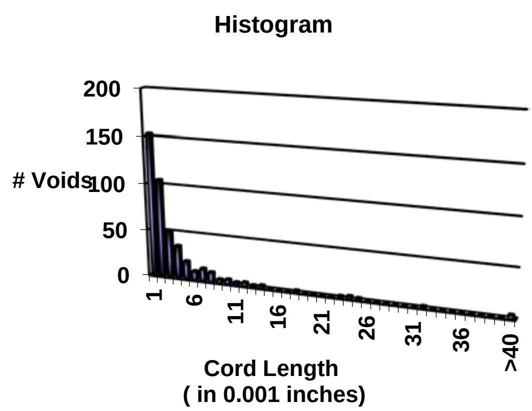
Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.

Sample Data:

Description: Hardened Concrete Cylinder
Dimensions: 102 mm (4") x 203 mm (8") diameter

Test Data: ASTM:C457 Linear Traverse Method, APS SOP 00LAB003 and ACI 116R

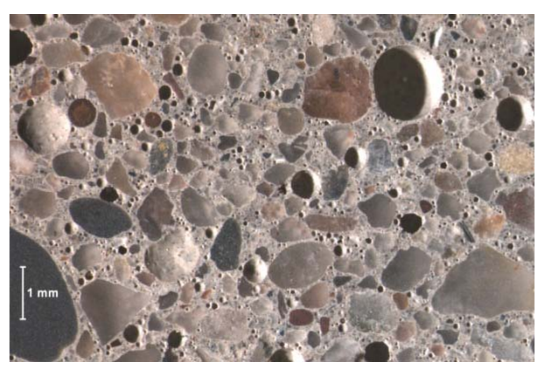
Air Void Content %	3.7
Entrained, % ≤ 0.040”	3.3
Entrapped, %> 0.040”	0.4
Air Voids/inch	8.57
Specific Surface, in2/in3	930
Spacing Factor, inches	0.006
Paste Content, % estimated	26.0
Magnification	50x
Traverse Length, inches	51
Test Date	06/25/2010



The test sample will be retained for at least 30 days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. Test results relate only to the item tested.

Report Prepared By:

Scott Wolter, PG
President
MN License #30024



Magnification: 15x
Description: Overall hardened air content, 3.7% total

AMERICAN ENGINEERING TESTING, INC.

AIR VOID ANALYSIS

PROJECT:
Truck Transit Air Content Study

REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

ATTN: Maria Masten
DATE: November 29, 2010

AET PROJECT NO: 28-00182

Sample Number: Task 2 Batch 1 (60 min.)

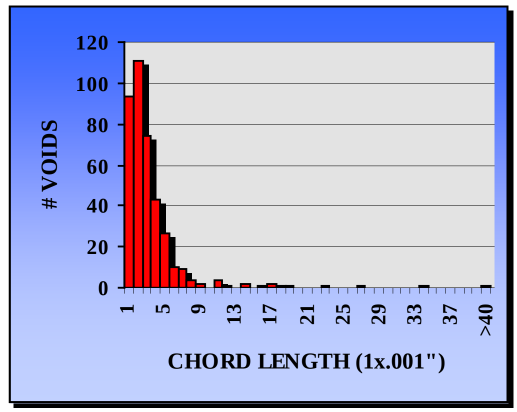
Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.

Sample Data

Description:	Hardened Concrete Cylinder
Dimensions:	102m (4”) diameter by 205mm (8”) long

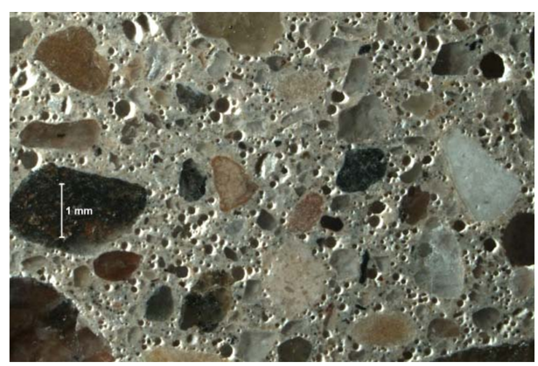
Test Data: By ASTM C:457

Air Void Content %	4.3
Entrained, % < 0.040”(1mm)	4.2
Entrapped, %> 0.040”(1mm)	0.1
Air Voids/inch	13.0
Specific Surface, in^2/in^3	1180
Spacing Factor, inches	0.004
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	30
Test Date	11/22/2010



Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023



Magnification: 10x
Description: Hardened air void system.

American Engineering Testing, Inc.

AIR VOID ANALYSIS

PROJECT:
Truck Transit Air Content Study

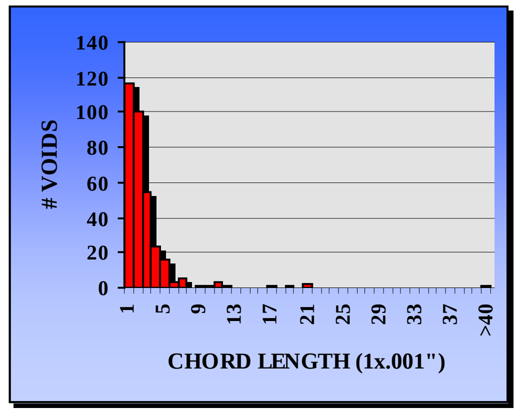
REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

ATTN: Maria Masten
DATE: November 29, 2010

AET PROJECT NO: 28-00182

Sample Number: Task 2 Batch 1 (120 min.)

Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.



Sample Data

Description: Hardened Concrete Cylinder

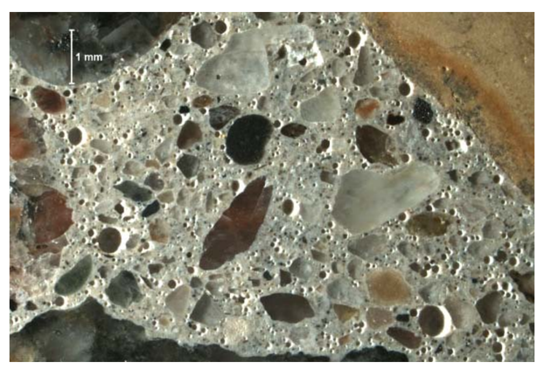
Dimensions: 102m (4") diameter by 205mm (8") long

Test Data:

Air Void Content %	3.3
Entrained, % < 0.040"(1mm)	2.8
Entrapped, %> 0.040"(1mm)	0.5
Air Voids/inch	11.0
Specific Surface, in^2/in^3	1310
Spacing Factor, inches	0.004
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	30
Test Date	11/23/2010

Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023



Magnification: 10x
Description: Hardened air void system.

AIR VOID ANALYSIS

PROJECT:
Truck Transit Air Content Study

REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

ATTN: Maria Masten
DATE: November 29, 2010

AET PROJECT NO: 28-00182

Sample Number: Task 2 Batch 2 (60 min.)

Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.

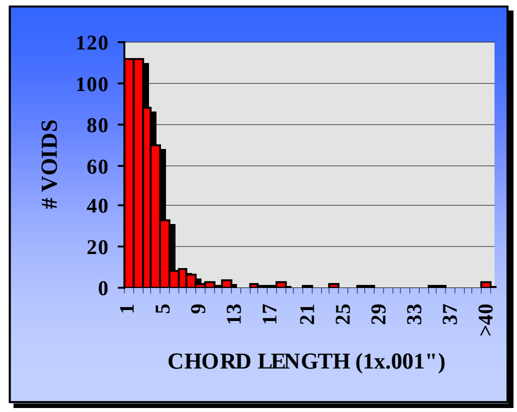
Sample Data

Description: Hardened Concrete Cylinder

Dimensions: 102m (4”) diameter by 205mm (8”) long

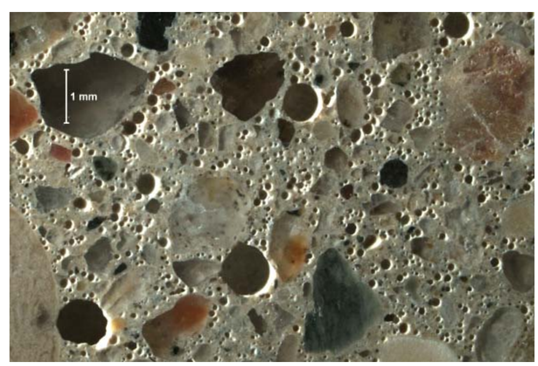
Test Data:

Air Void Content %	6.0
Entrained, % < 0.040”(1mm)	5.4
Entrapped, %> 0.040”(1mm)	0.6
Air Voids/inch	15.5
Specific Surface, in^2/in^3	1040
Spacing Factor, inches	0.004
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	30
Test Date	11/22/2010



Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023



Magnification: 10x
Description: Hardened air void system.

AIR VOID ANALYSIS

American Engineering Testing, Inc.

PROJECT:
Truck Transit Air Content Study

REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

ATTN: Maria Masten

AET PROJECT NO: 28-00182

DATE: November 29, 2010

Sample Number: Task 2 Batch 2 (120 min.)

Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.

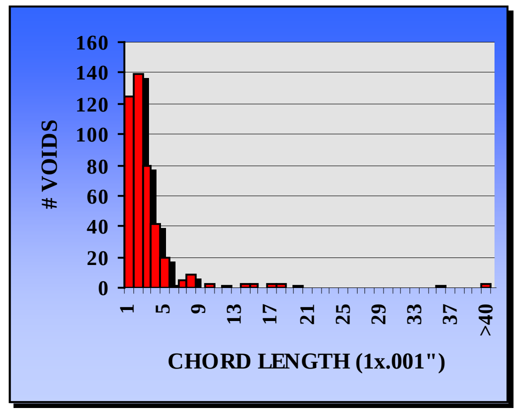
Sample Data

Description: Hardened Concrete Cylinder

Dimensions: 102m (4”) diameter by 205mm (8”) long

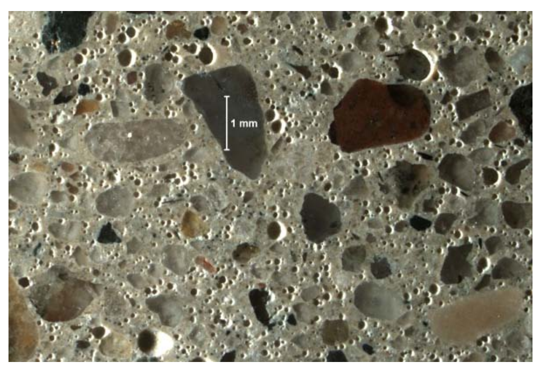
Test Data:

Air Void Content %	4.6
Entrained, % < 0.040”(1mm)	4.1
Entrapped, %> 0.040”(1mm)	0.5
Air Voids/inch	14.6
Specific Surface, in^2/in^3	1250
Spacing Factor, inches	0.004
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	30
Test Date	11/23/2010



Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023



Magnification: 10x
Description: Hardened air void system.

AMERICAN ENGINEERING TESTING, INC.

AIR VOID ANALYSIS

PROJECT:
Truck Transit Air Content Study

REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

ATTN: Maria Masten
DATE: November 29, 2010

AET PROJECT NO: 28-00182

Sample Number: Task 2 Batch 3 (60 min.)

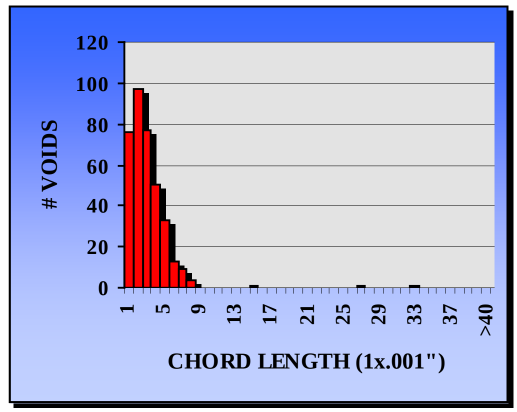
Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.

Sample Data

Description: Hardened Concrete Cylinder
Dimensions: 102m (4”) diameter by 205mm (8”) long

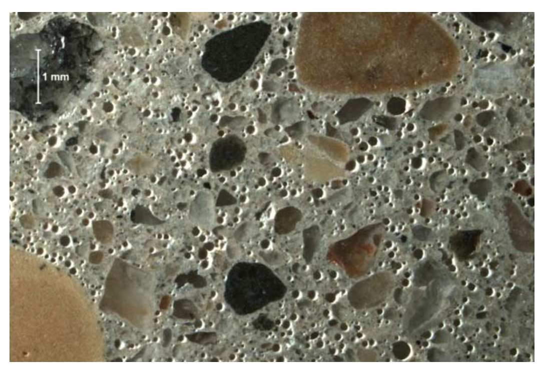
Test Data:

Air Void Content %	3.7
Entrained, % < 0.040”(1mm)	3.7
Entrapped, %> 0.040”(1mm)	0.0
Air Voids/inch	12.1
Specific Surface, in^2/in^3	1300
Spacing Factor, inches	0.004
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	30
Test Date	11/22/2010



Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023



Magnification: 10x
Description: Hardened air void system.

AIR VOID ANALYSIS

PROJECT:
Truck Transit Air Content Study

REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

ATTN: Maria Masten
DATE: November 29, 2010

AET PROJECT NO: 28-00182

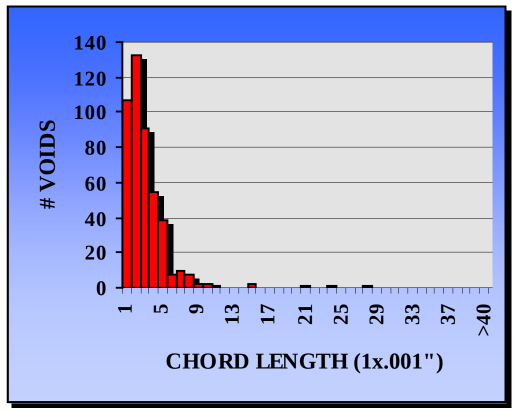
Sample Number: Task 2 Batch 3 (120 min.)
Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.

Sample Data

Description: Hardened Concrete Cylinder
Dimensions: 102m (4”) diameter by 205mm (8”) long

Test Data:

Air Void Content %	4.6
Entrained, % < 0.040”(1mm)	4.6
Entrapped, %> 0.040”(1mm)	0.0
Air Voids/inch	15.3
Specific Surface, in^2/in^3	1330
Spacing Factor, inches	0.004
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	30
Test Date	11/22/2010



Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023

Magnification: 10x
Description: Hardened air void system.

AIR VOID ANALYSIS

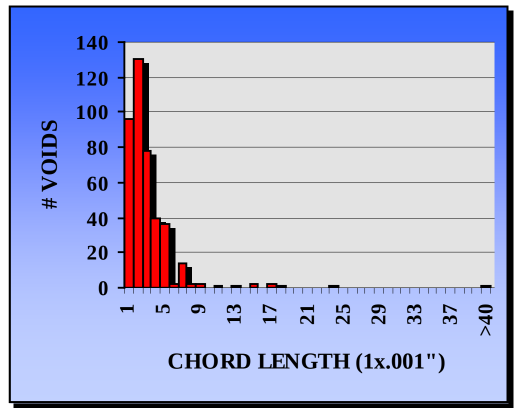
PROJECT:
Truck Transit Air Content Study

REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

ATTN: Maria Masten
DATE: November 29, 2010

AET PROJECT NO: 28-00182

Sample Number: Task 2 Batch 4 (60 min.)
Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.



Sample Data

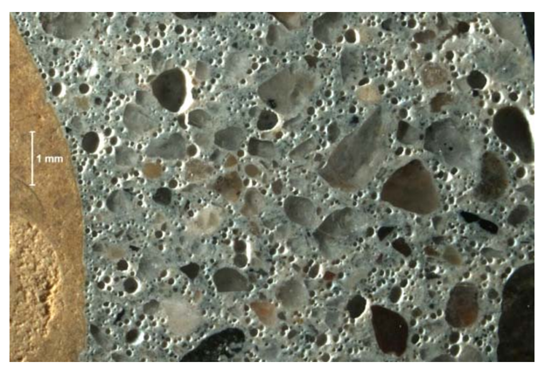
Description: Hardened Concrete Cylinder
Dimensions: 102m (4”) diameter by 205mm (8”) long

Test Data:

Air Void Content %	4.4
Entrained, % < 0.040”(1mm)	4.0
Entrapped, %> 0.040”(1mm)	0.4
Air Voids/inch	13.6
Specific Surface, in^2/in^3	1250
Spacing Factor, inches	0.004
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	30
Test Date	11/22/2010

Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023



Magnification: 10x
Description: Hardened air void system.

AIR VOID ANALYSIS

PROJECT:
Truck Transit Air Content Study

REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

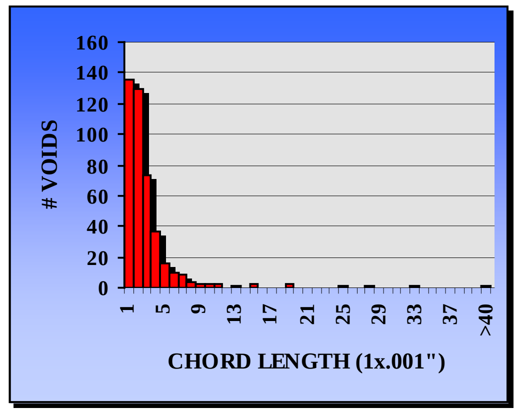
ATTN: Maria Masten
DATE: November 29, 2010

AET PROJECT NO: 28-00182

Sample Number: Task 2 Batch 4 (120 min.)
Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.

Sample Data

Description: Hardened Concrete Cylinder
Dimensions: 102m (4") diameter by 205mm (8") long

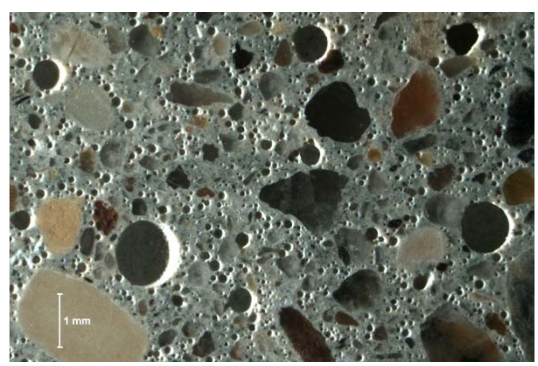


Test Data:

Air Void Content %	4.2
Entrained, % < 0.040"(1mm)	4.1
Entrapped, %> 0.040"(1mm)	0.1
Air Voids/inch	14.3
Specific Surface, in^2/in^3	1350
Spacing Factor, inches	0.004
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	30
Test Date	11/22/2010

Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023



Magnification: 10x
Description: Hardened air void system.

AIR VOID ANALYSIS

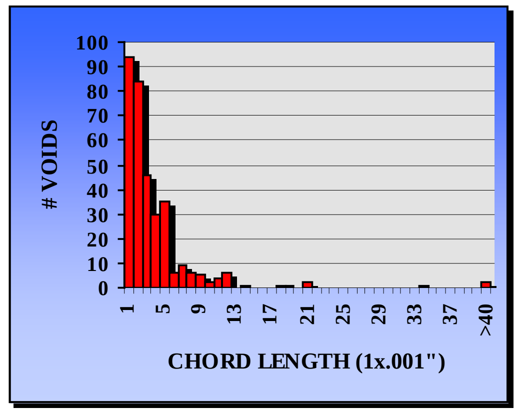
PROJECT:
Truck Transit Air Content Study

REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

ATTN: Maria Masten
DATE: November 30, 2010

AET PROJECT NO: 28-00182

Sample Number: Task 3 Batch 5 (60 min.)
Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.



Sample Data

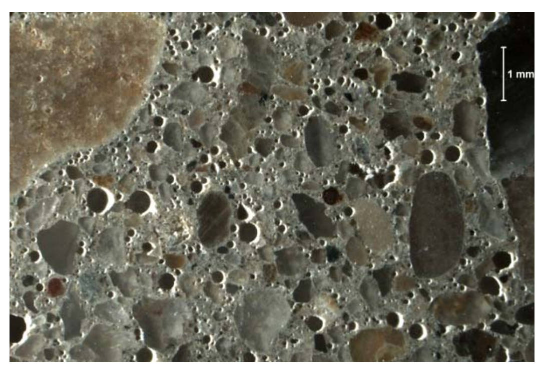
Description: Hardened Concrete Cylinder
Dimensions: 102m (4”) diameter by 205mm (8”) long

Test Data:

Air Void Content %	4.5
Entrained, % < 0.040”(1mm)	3.8
Entrapped, %> 0.040”(1mm)	0.7
Air Voids/inch	11.2
Specific Surface, in^2/in^3	990
Spacing Factor, inches	0.005
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	30
Test Date	11/30/2010

Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023



Magnification: 10x
Description: Hardened air void system.

AMERICAN ENGINEERING TESTING, INC.

AIR VOID ANALYSIS

PROJECT:
Truck Transit Air Content Study

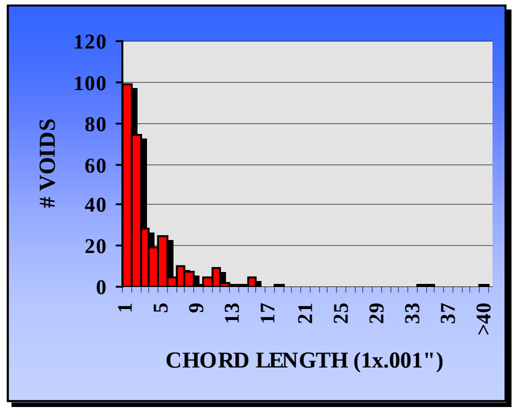
REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

ATTN: Maria Masten
DATE: November 30, 2010

AET PROJECT NO: 28-00182

Sample Number: Task 3 Batch 5 (120 min.)

Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.



Sample Data

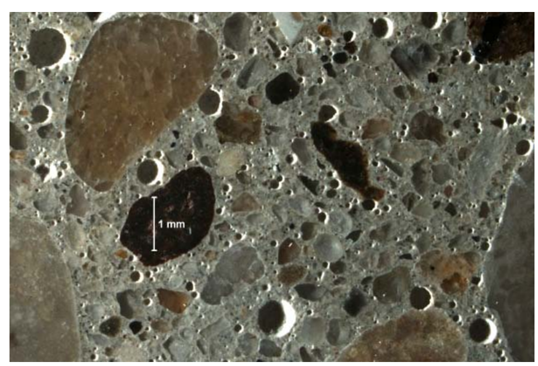
Description: Hardened Concrete Cylinder
Dimensions: 102m (4”) diameter by 205mm (8”) long

Test Data:

Air Void Content %	3.7
Entrained, % < 0.040”(1mm)	3.5
Entrapped, %> 0.040”(1mm)	0.2
Air Voids/inch	9.8
Specific Surface, in^2/in^3	1070
Spacing Factor, inches	0.005
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	30
Test Date	11/30/2010

Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023



Magnification: 10x
Description: Hardened air void system.

AMERICAN ENGINEERING TESTING, INC.

AIR VOID ANALYSIS

PROJECT:
Truck Transit Air Content Study

REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

ATTN: Maria Masten
DATE: November 30, 2010

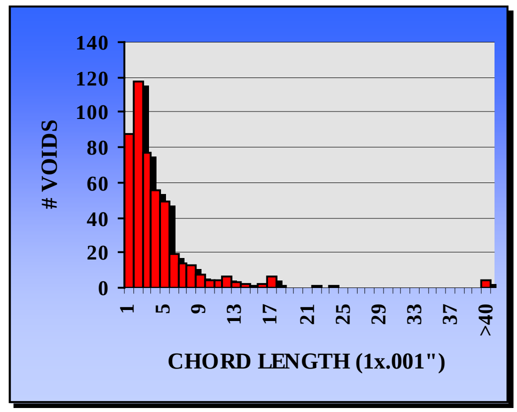
AET PROJECT NO: 28-00182

Sample Number: Task 3 Batch 6 (60 min.)
Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.

Sample Data
Description: Hardened Concrete Cylinder
Dimensions: 102m (4") diameter by 205mm (8") long

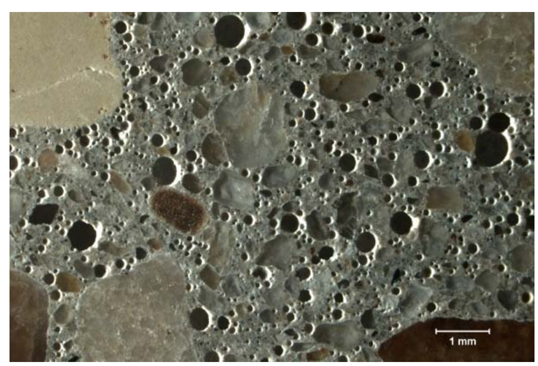
Test Data:

Air Void Content %	6.8
Entrained, % < 0.040"(1mm)	6.1
Entrapped, %> 0.040"(1mm)	0.7
Air Voids/inch	19.9
Specific Surface, in^2/in^3	930
Spacing Factor, inches	0.004
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	30
Test Date	11/30/2010



Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023



Magnification: 10x
Description: Hardened air void system.

AMERICAN ENGINEERING TESTING, INC.

AIR VOID ANALYSIS

PROJECT:
Truck Transit Air Content Study

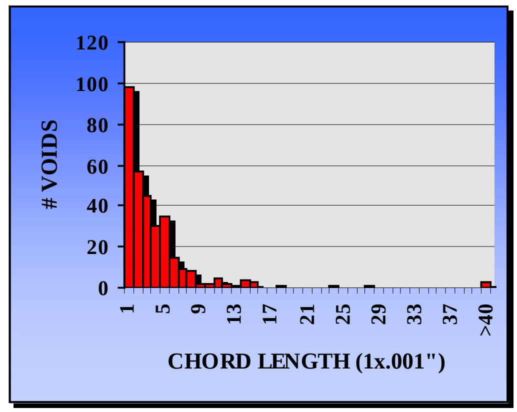
REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

ATTN: Maria Masten
DATE: November 30, 2010

AET PROJECT NO: 28-00182

Sample Number: Task 3 Batch 6 (120 min.)

Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.



Sample Data

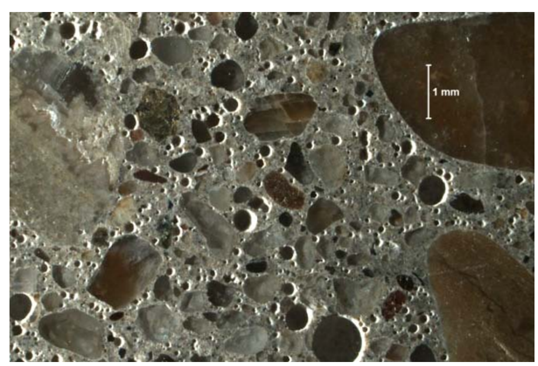
Description: Hardened Concrete Cylinder
Dimensions: 102m (4") diameter by 205mm (8") long

Test Data:

Air Void Content %	4.6
Entrained, % < 0.040"(1mm)	3.9
Entrapped, %> 0.040"(1mm)	0.7
Air Voids/inch	10.7
Specific Surface, in^2/in^3	940
Spacing Factor, inches	0.005
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	30
Test Date	11/30/2010

Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023



Magnification: 10x
Description: Hardened air void system.

AIR VOID ANALYSIS

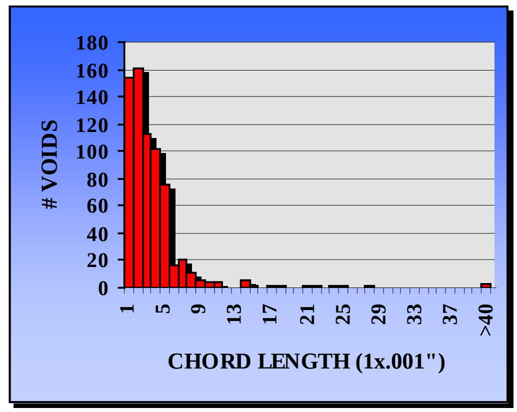
PROJECT:
Truck Transit Air Content Study

REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

ATTN: Maria Masten
DATE: November 29, 2010

AET PROJECT NO: 28-00182

Sample Number: Task 3 Batch 7 (60 min.)
Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.



Sample Data

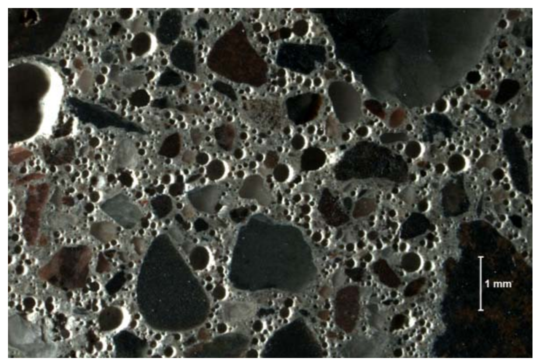
Description: Hardened Concrete Cylinder
Dimensions: 102m (4") diameter by 205mm (8") long

Test Data:

Air Void Content %	8.4
Entrained, % < 0.040"(1mm)	7.8
Entrapped, %> 0.040"(1mm)	0.6
Air Voids/inch	22.8
Specific Surface, in^2/in^3	1080
Spacing Factor, inches	0.003
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	30
Test Date	11/29/2010

Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023



Magnification: 10x
Description: Hardened air void system.

AIR VOID ANALYSIS

PROJECT:
Truck Transit Air Content Study

REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

ATTN: Maria Masten
DATE: November 29, 2010

AET PROJECT NO: 28-00182

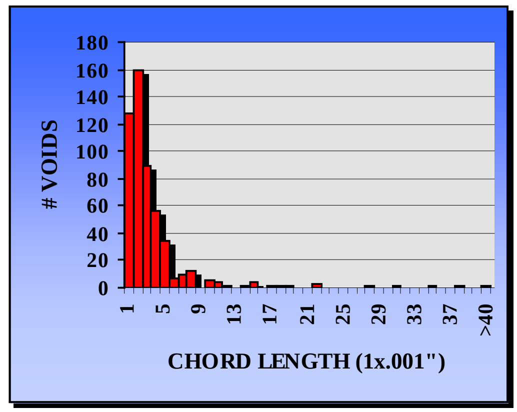
Sample Number: Task 3 Batch 7 (120 min.)
Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.

Sample Data

Description: Hardened Concrete Cylinder
Dimensions: 102m (4”) diameter by 205mm (8”) long

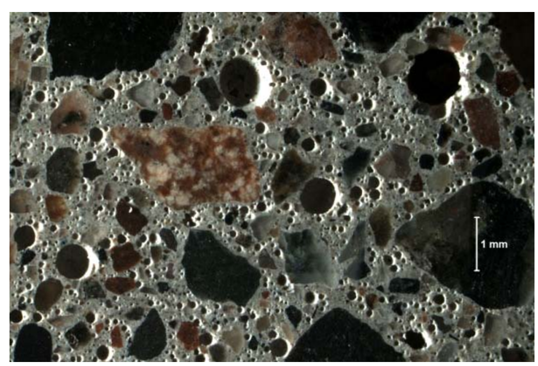
Test Data:

Air Void Content %	6.4
Entrained, % < 0.040”(1mm)	6.0
Entrapped, %> 0.040”(1mm)	0.4
Air Voids/inch	17.6
Specific Surface, in^2/in^3	1100
Spacing Factor, inches	0.004
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	30
Test Date	11/29/2010



Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023



Magnification: 10x
Description: Hardened air void system.

AIR VOID ANALYSIS

AMERICAN ENGINEERING TESTING, INC.

PROJECT:
Truck Transit Air Content Study

REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

ATTN: Maria Masten
DATE: November 29, 2010

AET PROJECT NO: 28-00182

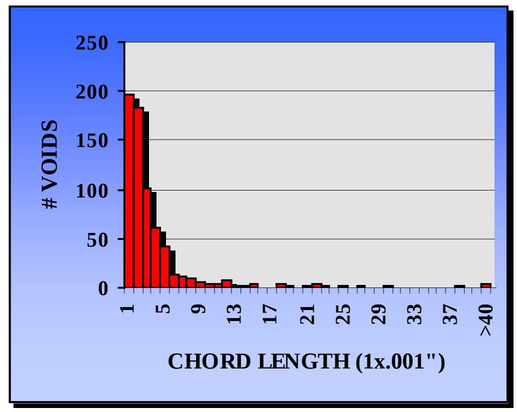
Sample Number: Task 3 Batch 8 (60 min.)
Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.

Sample Data

Description: Hardened Concrete Cylinder
Dimensions: 102m (4”) diameter by 205mm (8”) long

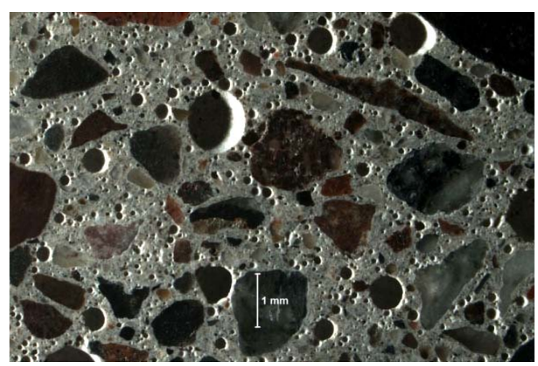
Test Data:

Air Void Content %	8.3
Entrained, % < 0.040”(1mm)	7.4
Entrapped, %> 0.040”(1mm)	0.9
Air Voids/inch	22.2
Specific Surface, in^2/in^3	1070
Spacing Factor, inches	0.003
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	30
Test Date	11/29/2010



Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023



Magnification: 10x
Description: Hardened air void system.

AIR VOID ANALYSIS

PROJECT:
Truck Transit Air Content Study

REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

ATTN: Maria Masten
DATE: November 29, 2010

AET PROJECT NO: 28-00182

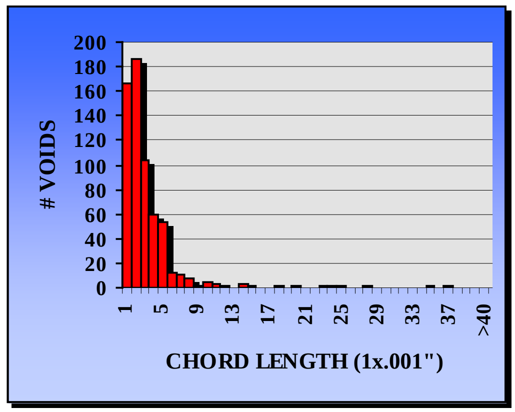
Sample Number: Task 3 Batch 8 (120 min.)
Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.

Sample Data

Description: Hardened Concrete Cylinder
Dimensions: 102m (4”) diameter by 205mm (8”) long

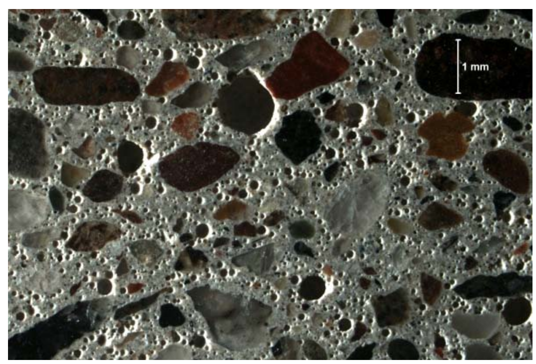
Test Data:

Air Void Content %	6.7
Entrained, % < 0.040”(1mm)	6.7
Entrapped, %> 0.040”(1mm)	0.0
Air Voids/inch	20.8
Specific Surface, in^2/in^3	1240
Spacing Factor, inches	0.003
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	30
Test Date	11/29/2010



Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023



Magnification: 10x
Description: Hardened air void system.

AIR VOID ANALYSIS

PROJECT:
Truck Transit Air Content Study

REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

ATTN: Maria Masten
DATE: December 2, 2010

AET PROJECT NO: 28-00182

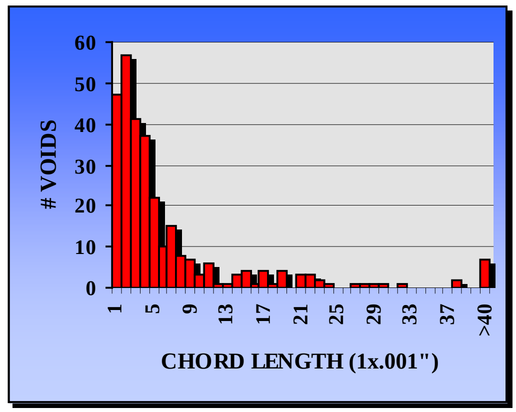
Sample Number: Task 3 Batch 9 (60 min.)
Conformance: The sample contains an air void system which is generally consistent with current technology for freeze-thaw resistance.

Sample Data

Description: Hardened Concrete Cylinder
Dimensions: 102m (4”) diameter by 205mm (8”) long

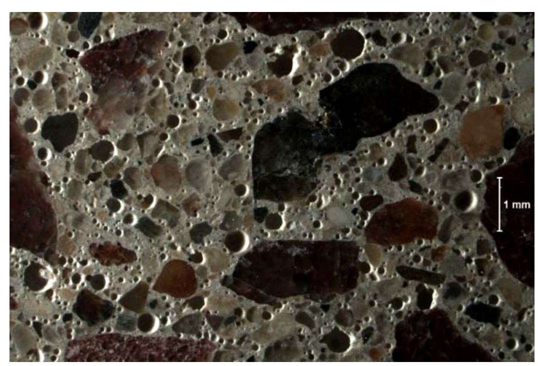
Test Data:

Air Void Content %	6.8
Entrained, % < 0.040”(1mm)	5.5
Entrapped, %> 0.040”(1mm)	1.3
Air Voids/inch	9.8
Specific Surface, in^2/in^3	570
Spacing Factor, inches	0.007
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	30
Test Date	12/2/2010



Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023



Magnification: 10x
Description: Hardened air void system.

AIR VOID ANALYSIS

PROJECT:
Truck Transit Air Content Study

REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

ATTN: Maria Masten
DATE: December 2, 2010

AET PROJECT NO: 28-00182

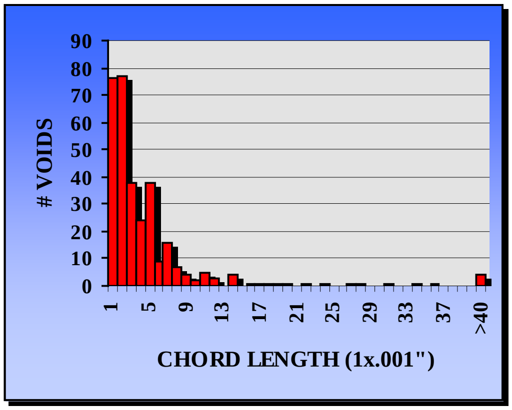
Sample Number: Task 3 Batch 9 (120 min.)
Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.

Sample Data

Description: Hardened Concrete Cylinder
Dimensions: 102m (4”) diameter by 205mm (8”) long

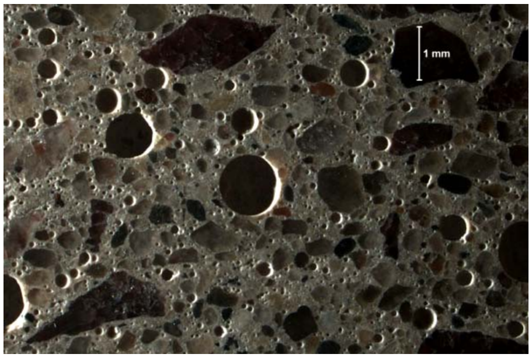
Test Data:

Air Void Content %	5.5
Entrained, % < 0.040”(1mm)	4.5
Entrapped, %> 0.040”(1mm)	1.0
Air Voids/inch	10.6
Specific Surface, in^2/in^3	780
Spacing Factor, inches	0.006
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	30
Test Date	12/2/2010



Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023



Magnification: 10x
Description: Hardened air void system.

AIR VOID ANALYSIS

PROJECT:
Truck Transit Air Content Study

REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

ATTN: Maria Masten

AET PROJECT NO: 28-00182

DATE: December 2, 2010

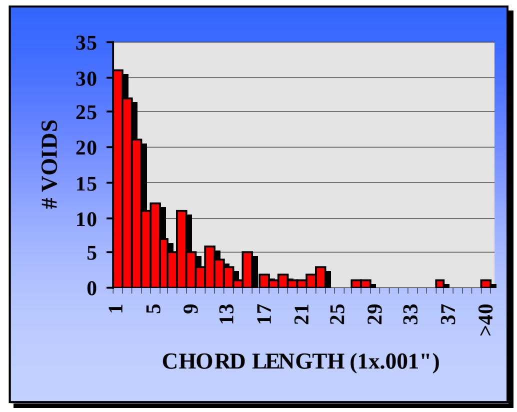
Sample Number: Task 3 Batch 10 (60 min.)

Conformance: The sample contains an air void system which is generally not consistent with current technology for freeze-thaw resistance.

Sample Data

Description: Hardened Concrete Cylinder

Dimensions: 102m (4”) diameter by 205mm (8”) long

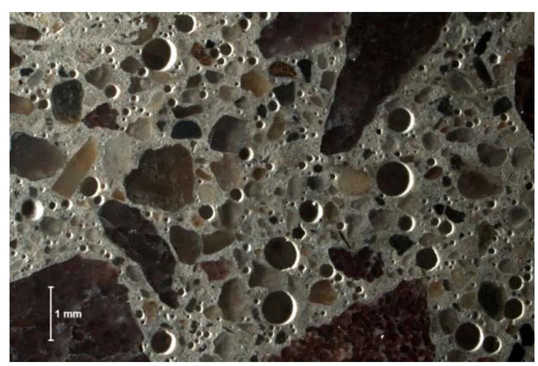


Test Data:

Air Void Content %	3.8
Entrained, % < 0.040”(1mm)	3.6
Entrapped, %> 0.040”(1mm)	0.2
Air Voids/inch	5.6
Specific Surface, in^2/in^3	600
Spacing Factor, inches	0.009
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	30
Test Date	12/2/2010

Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023



Magnification: 10x
Description: Hardened air void system.

AIR VOID ANALYSIS

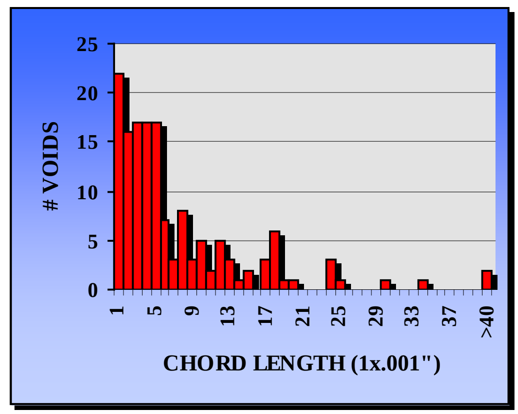
PROJECT:
Truck Transit Air Content Study

REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

ATTN: Maria Masten
DATE: December 2, 2010

AET PROJECT NO: 28-00182

Sample Number: Task 3 Batch 10 (120 min.)
Conformance: The sample contains an air void system which is not consistent with current technology for freeze-thaw resistance.



Sample Data

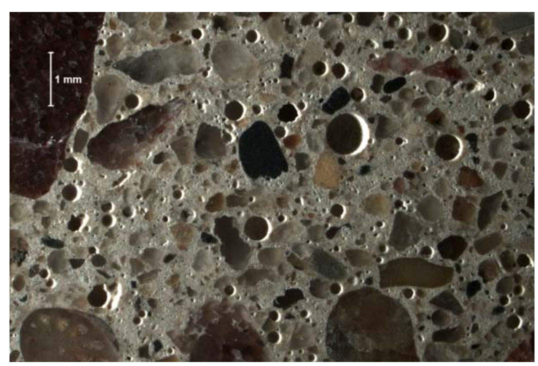
Description: Hardened Concrete Cylinder
Dimensions: 102m (4”) diameter by 205mm (8”) long

Test Data:

Air Void Content %	3.6
Entrained, % < 0.040”(1mm)	3.3
Entrapped, %> 0.040”(1mm)	0.3
Air Voids/inch	4.9
Specific Surface, in^2/in^3	540
Spacing Factor, inches	0.010
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	30
Test Date	12/2/2010

Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023



Magnification: 10x
Description: Hardened air void system.

AMERICAN ENGINEERING TESTING, INC.

AIR VOID ANALYSIS

PROJECT:
Truck Transit Air Content Study

REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

ATTN: Maria Masten
DATE: February 15, 2011

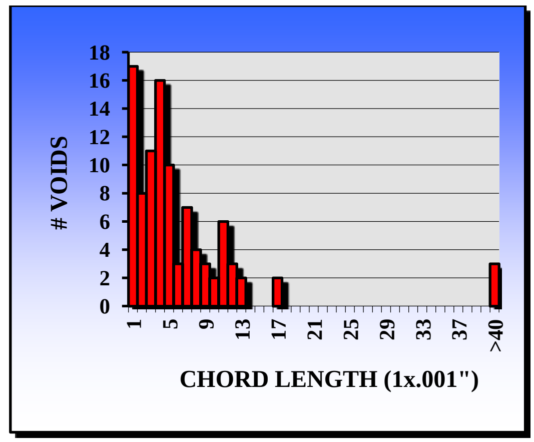
AET PROJECT NO: 28-00182

Sample Number: Task 3 Batch 11 (60 min.)
Conformance: The sample contains an air void system which does not appear consistent with current technology for freeze-thaw resistance.

Sample Data
Description: Hardened Concrete Cylinder
Dimensions: 102m (4”) diameter by 205mm (8”) long

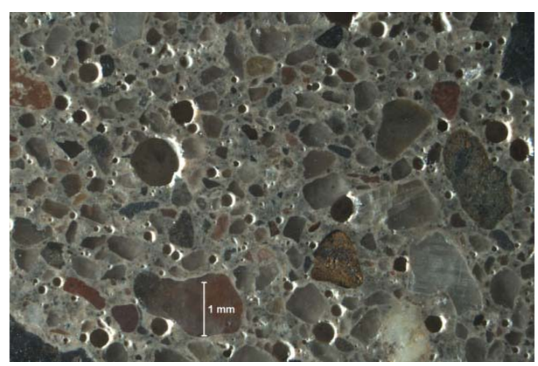
Test Data:

Air Void Content %	3.0
Entrained, % < 0.040”(1mm)	2.3
Entrapped, %> 0.040”(1mm)	0.7
Air Voids/inch	4.6
Specific Surface, in^2/in^3	610
Spacing Factor, inches	0.010
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	21
Test Date	2/14/2011



Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023



Magnification: 10x
Description: Hardened air void system.

AIR VOID ANALYSIS

PROJECT:
Truck Transit Air Content Study

REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

ATTN: Maria Masten
DATE: February 15, 2011

AET PROJECT NO: 28-00182

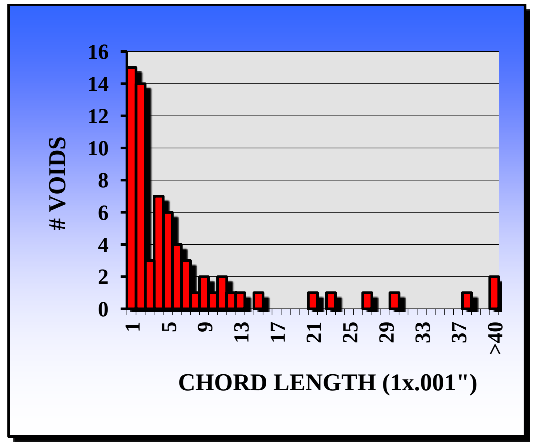
Sample Number: Task 3 Batch 11 (120 min.)
Conformance: The sample contains an air void system which does not appear consistent with current technology for freeze-thaw resistance.

Sample Data

Description: Hardened Concrete Cylinder
Dimensions: 102m (4") diameter by 205mm (8") long

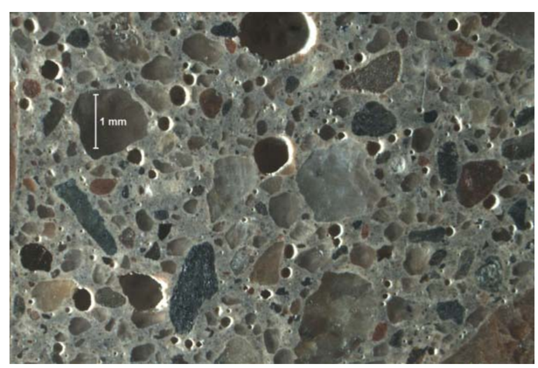
Test Data:

Air Void Content %	2.5
Entrained, % < 0.040"(1mm)	1.9
Entrapped, %> 0.040"(1mm)	0.6
Air Voids/inch	3.2
Specific Surface, in^2/in^3	520
Spacing Factor, inches	0.012
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	21
Test Date	2/11/2011



Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023



Magnification: 10x
Description: Hardened air void system.

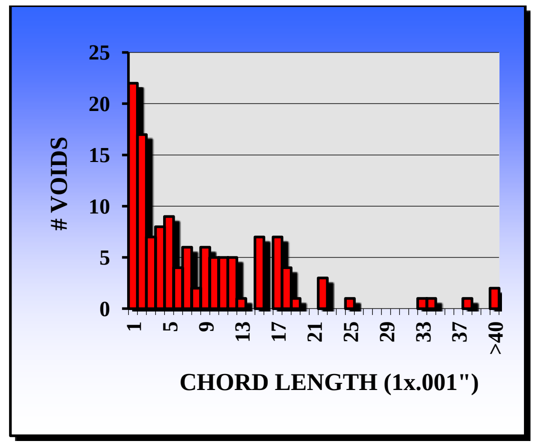
AIR VOID ANALYSIS

PROJECT:
Truck Transit Air Content Study

REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

ATTN: Maria Masten
AET PROJECT NO: 28-00182
DATE: February 15, 2011

Sample Number: Task 3 Batch 12 (60 min.)
Conformance: The sample contains an air void system which does not appear consistent with current technology for freeze-thaw resistance.



Sample Data

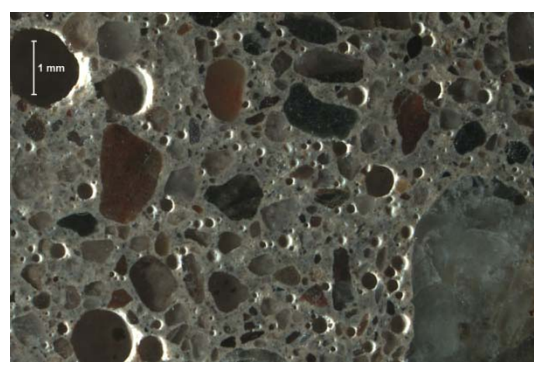
Description: Hardened Concrete Cylinder
Dimensions: 102m (4") diameter by 205mm (8") long

Test Data:

Air Void Content %	5.4
Entrained, % < 0.040"(1mm)	4.7
Entrapped, %> 0.040"(1mm)	0.7
Air Voids/inch	6.0
Specific Surface, in^2/in^3	450
Spacing Factor, inches	0.010
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	21
Test Date	2/14/2011

Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023



Magnification: 10x
Description: Hardened air void system.

AMERICAN ENGINEERING TESTING, INC.

AIR VOID ANALYSIS

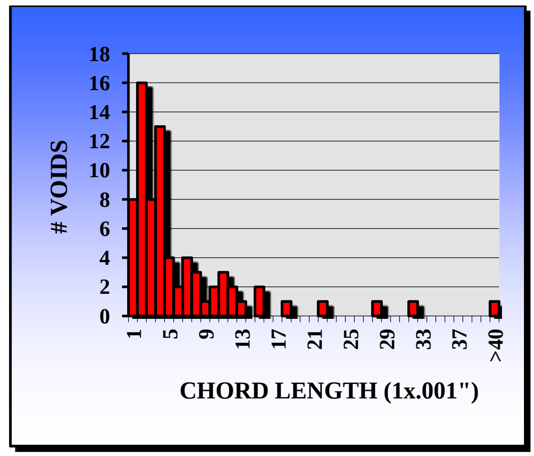
PROJECT:
Truck Transit Air Content Study

REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

ATTN: Maria Masten
DATE: February 15, 2011

AET PROJECT NO: 28-00182

Sample Number: Task 3 Batch 12 (120 min.)
Conformance: The sample contains an air void system which does not appear consistent with current technology for freeze-thaw resistance.



Sample Data

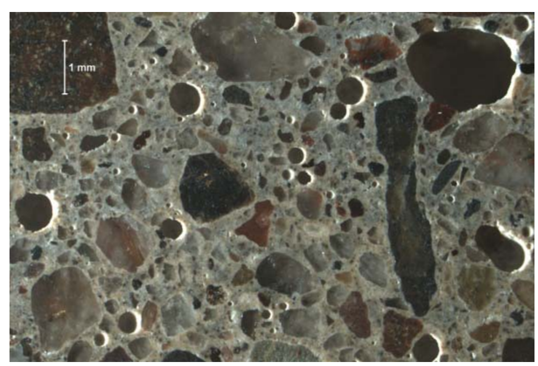
Description: Hardened Concrete Cylinder
Dimensions: 102m (4") diameter by 205mm (8") long

Test Data:

Air Void Content %	2.4
Entrained, % < 0.040"(1mm)	2.0
Entrapped, %> 0.040"(1mm)	0.4
Air Voids/inch	3.5
Specific Surface, in^2/in^3	590
Spacing Factor, inches	0.011
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	21
Test Date	2/11/2011

Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023



Magnification: 10x
Description: Hardened air void system.

AIR VOID ANALYSIS

PROJECT:
Truck Transit Air Content Study

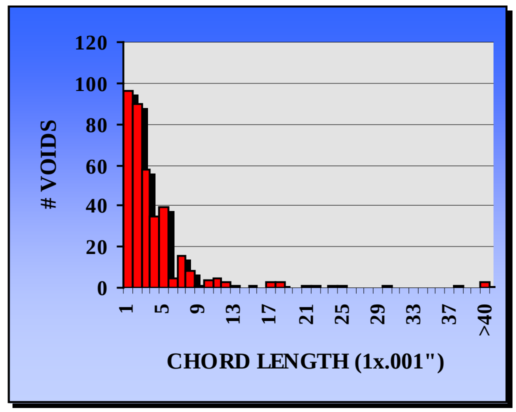
REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

ATTN: Maria Masten
DATE: December 6, 2010

AET PROJECT NO: 28-00182

Sample Number: Task 3 Batch 13 (60 min.)

Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.



Sample Data

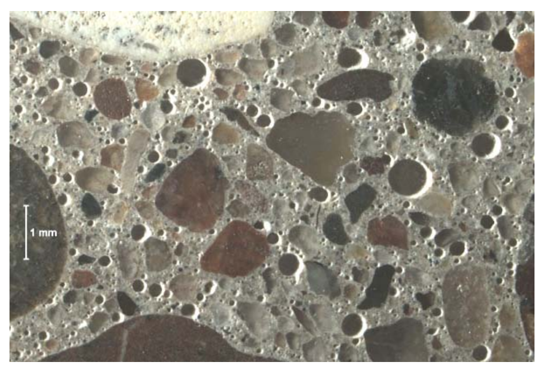
Description: Hardened Concrete Cylinder
Dimensions: 102m (4") diameter by 205mm (8") long

Test Data:

Air Void Content %	5.8
Entrained, % < 0.040"(1mm)	4.7
Entrapped, %> 0.040"(1mm)	1.1
Air Voids/inch	12.6
Specific Surface, in^2/in^3	870
Spacing Factor, inches	0.005
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	30
Test Date	12/6/2010

Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023



Magnification: 10x
Description: Hardened air void system.

AMERICAN ENGINEERING TESTING, INC.

AIR VOID ANALYSIS

PROJECT:
Truck Transit Air Content Study

REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

ATTN: Maria Masten
DATE: December 6, 2010

AET PROJECT NO: 28-00182

Sample Number: Task 3 Batch 13 (120 min.)

Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.

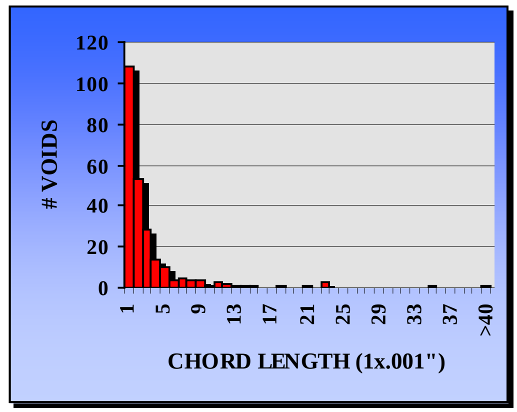
Sample Data

Description: Hardened Concrete Cylinder

Dimensions: 102m (4”) diameter by 205mm (8”) long

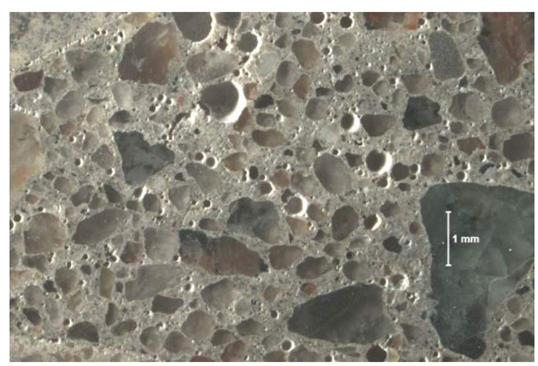
Test Data:

Air Void Content %	2.8
Entrained, % < 0.040”(1mm)	2.6
Entrapped, %> 0.040”(1mm)	0.1
Air Voids/inch	8.2
Specific Surface, in^2/in^3	1190
Spacing Factor, inches	0.005
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	30
Test Date	12/6/2010



Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023



Magnification: 10x
Description: Hardened air void system.

AIR VOID ANALYSIS

PROJECT:
Truck Transit Air Content Study

REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

ATTN: Maria Masten
DATE: December 10, 2010

AET PROJECT NO: 28-00182

Sample Number: Task 3 Batch 14 (60 min.)

Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.

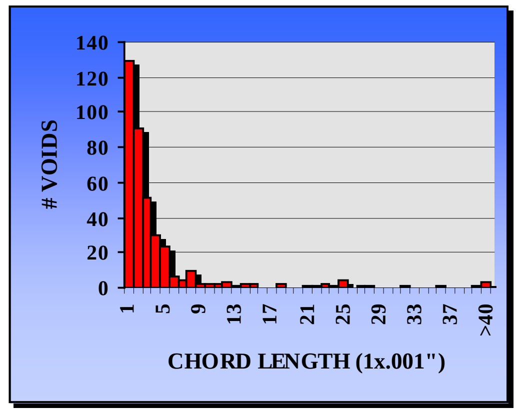
Sample Data

Description: Hardened Concrete Cylinder

Dimensions: 102m (4”) diameter by 205mm (8”) long

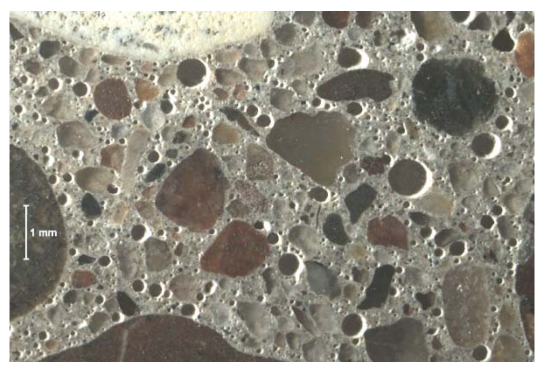
Test Data:

Air Void Content %	5.2
Entrained, % < 0.040”(1mm)	4.7
Entrapped, %> 0.040”(1mm)	0.5
Air Voids/inch	12.6
Specific Surface, in^2/in^3	950
Spacing Factor, inches	0.005
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	30
Test Date	12/10/2010



Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023



Magnification: 15x
Description: Hardened air void system.

AIR VOID ANALYSIS

PROJECT:
Truck Transit Air Content Study

REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

AET PROJECT NO: 28-00182

ATTN: Maria Masten
DATE: December 10, 2010

Sample Number: Task 3 Batch 14 (120 min.)

Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.

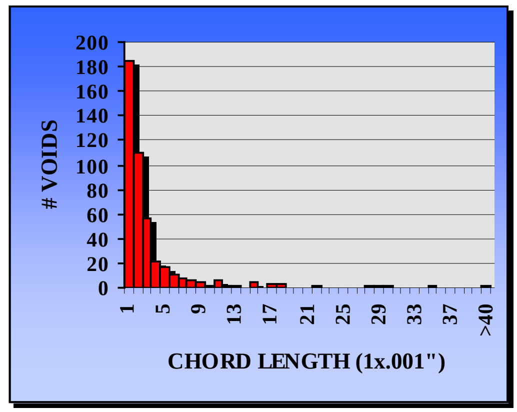
Sample Data

Description: Hardened Concrete Cylinder

Dimensions: 102m (4") diameter by 205mm (8") long

Test Data:

Air Void Content %	5.0
Entrained, % < 0.040"(1mm)	4.7
Entrapped, %> 0.040"(1mm)	0.3
Air Voids/inch	14.9
Specific Surface, in^2/in^3	1180
Spacing Factor, inches	0.004
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	30
Test Date	12/10/2010



Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023

Magnification: 15x
Description: Hardened air void system.

AIR VOID ANALYSIS

PROJECT:
Truck Transit Air Content Study

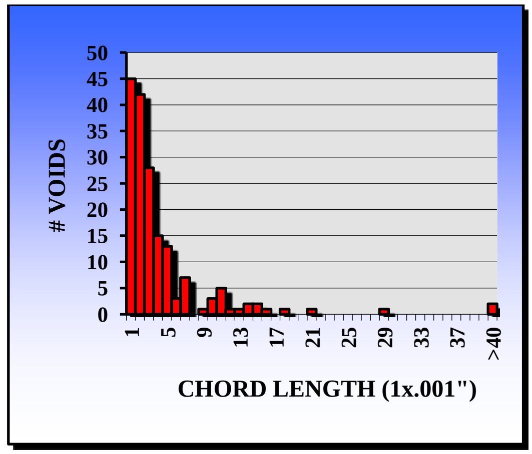
REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

ATTN: Maria Masten
DATE: February 15, 2011

AET PROJECT NO: 28-00182

Sample Number: Task 3 Batch 15 (60 min.)

Conformance: The sample contains an air void system which appears consistent with current technology for freeze-thaw resistance.



Sample Data

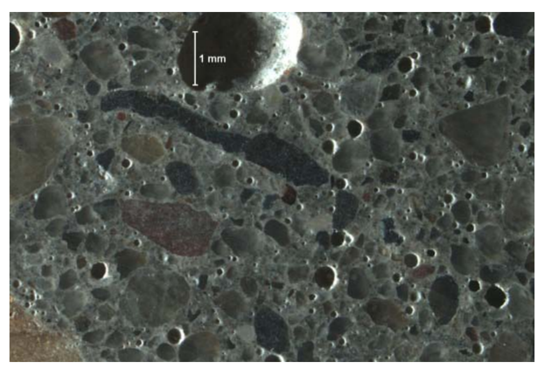
Description:	Hardened Concrete Cylinder
Dimensions:	102m (4") diameter by 205mm (8") long

Test Data:

Air Void Content %	4.2
Entrained, % < 0.040"(1mm)	3.2
Entrapped, %> 0.040"(1mm)	1.0
Air Voids/inch	8.3
Specific Surface, in^2/in^3	800
Spacing Factor, inches	0.006
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	21
Test Date	2/14/2011

Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023



Magnification: 10x
Description: Hardened air void system.

AIR VOID ANALYSIS

PROJECT:
Truck Transit Air Content Study

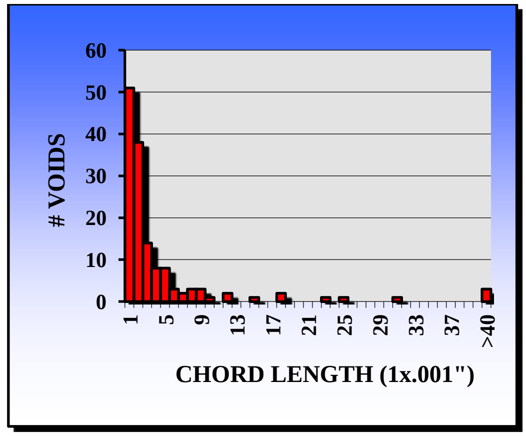
REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

ATTN: Maria Masten
DATE: February 15, 2011

AET PROJECT NO: 28-00182

Sample Number: Task 3 Batch 15 (120 min.)

Conformance: The sample contains an air void system which appears consistent with current technology for freeze-thaw resistance.



Sample Data

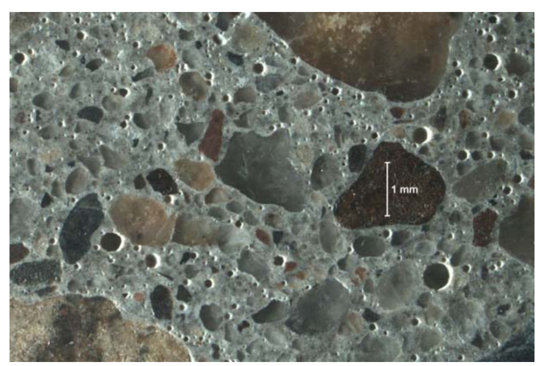
Description: Hardened Concrete Cylinder
Dimensions: 102m (4") diameter by 205mm (8") long

Test Data:

Air Void Content %	4.4
Entrained, % < 0.040"(1mm)	2.3
Entrapped, %> 0.040"(1mm)	2.1
Air Voids/inch	6.8
Specific Surface, in^2/in^3	610
Spacing Factor, inches	0.008
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	21
Test Date	2/14/2011

Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023



Magnification: 10x
Description: Hardened air void system.

AIR VOID ANALYSIS

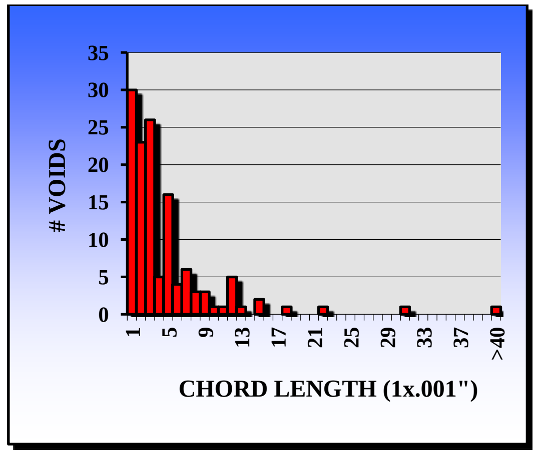
PROJECT:
Truck Transit Air Content Study

REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

ATTN: Maria Masten
DATE: February 15, 2011

AET PROJECT NO: 28-00182

Sample Number: Task 3 Batch 16 (60 min.)
Conformance: The sample contains an air void system which appears consistent with current technology for freeze-thaw resistance.



Sample Data

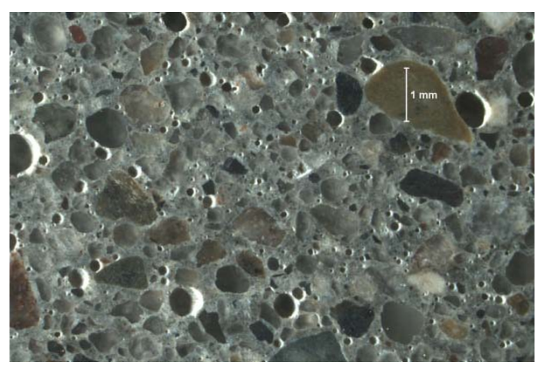
Description:	Hardened Concrete Cylinder
Dimensions:	102m (4") diameter by 205mm (8") long

Test Data:

Air Void Content %	3.0
Entrained, % < 0.040"(1mm)	2.7
Entrapped, %> 0.040"(1mm)	0.3
Air Voids/inch	6.2
Specific Surface, in^2/in^3	830
Spacing Factor, inches	0.007
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	21
Test Date	2/14/2011

Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023



Magnification: 10x
Description: Hardened air void system.

AIR VOID ANALYSIS

PROJECT:
Truck Transit Air Content Study

REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

ATTN: Maria Masten
DATE: February 15, 2011

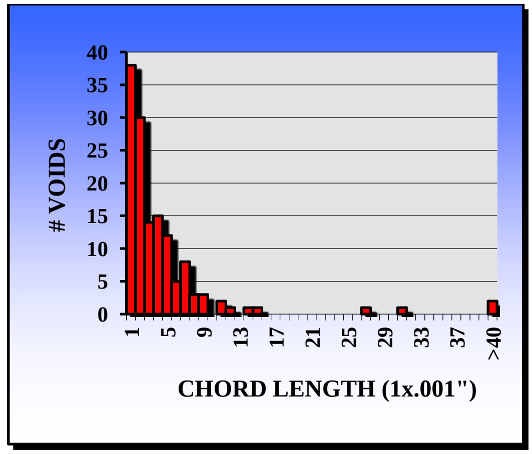
AET PROJECT NO: 28-00182

Sample Number: Task 3 Batch 16 (120 min.)
Conformance: The sample contains an air void system which appears consistent with current technology for freeze-thaw resistance.

Sample Data
Description: Hardened Concrete Cylinder
Dimensions: 102m (4”) diameter by 205mm (8”) long

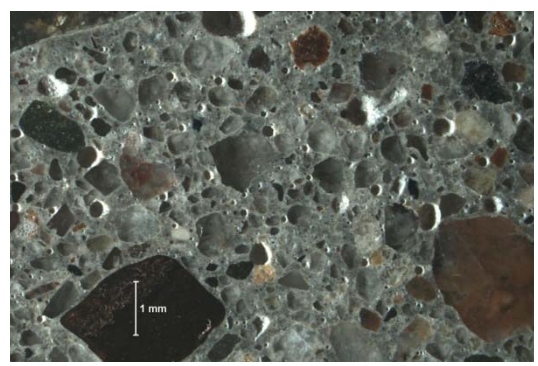
Test Data:

Air Void Content %	3.1
Entrained, % < 0.040”(1mm)	2.5
Entrapped, %> 0.040”(1mm)	0.6
Air Voids/inch	6.5
Specific Surface, in^2/in^3	860
Spacing Factor, inches	0.007
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	21
Test Date	2/14/2011



Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023



Magnification: 10x
Description: Hardened air void system.

AIR VOID ANALYSIS

PROJECT:
Truck Transit Air Content Study

REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

ATTN: Maria Masten
DATE: February 15, 2011

AET PROJECT NO: 28-00182

Sample Number: Task 3 Batch 17 (60 min.)

Conformance: The sample contains an air void system which appears consistent with current technology for freeze-thaw resistance.

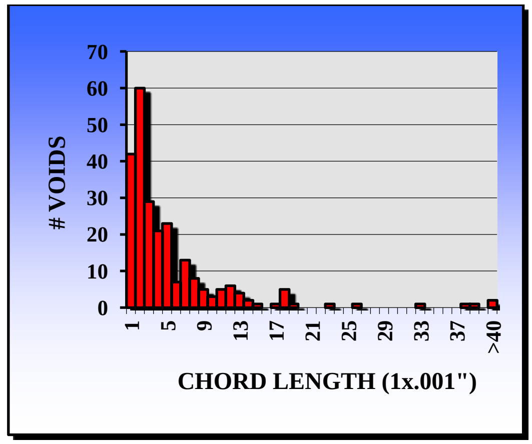
Sample Data

Description: Hardened Concrete Cylinder

Dimensions: 102m (4”) diameter by 205mm (8”) long

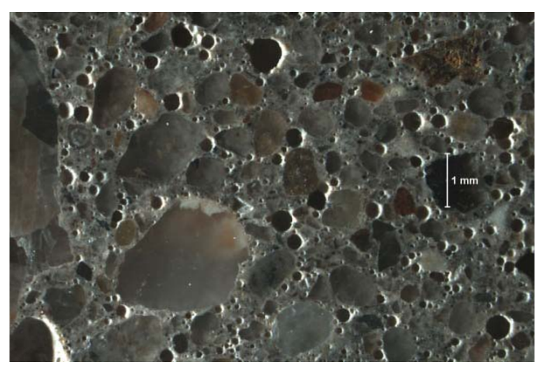
Test Data:

Air Void Content %	6.2
Entrained, % < 0.040”(1mm)	5.8
Entrapped, %> 0.040”(1mm)	0.4
Air Voids/inch	11.6
Specific Surface, in^2/in^3	740
Spacing Factor, inches	0.006
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	21
Test Date	2/11/2011



Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023



Magnification: 10x
Description: Hardened air void system.

AIR VOID ANALYSIS

PROJECT:
Truck Transit Air Content Study

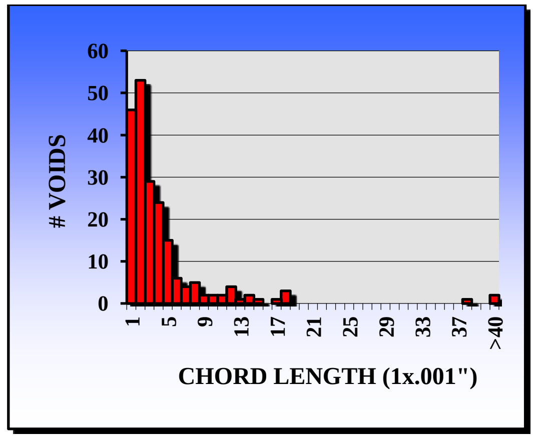
REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

ATTN: Maria Masten
DATE: February 15, 2011

AET PROJECT NO: 28-00182

Sample Number: Task 3 Batch 17 (120 min.)

Conformance: The sample contains an air void system which appears consistent with current technology for freeze-thaw resistance.



Sample Data

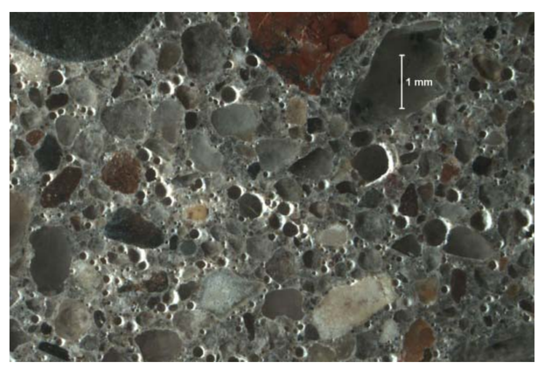
Description:	Hardened Concrete Cylinder
Dimensions:	102m (4”) diameter by 205mm (8”) long

Test Data:

Air Void Content %	4.6
Entrained, % < 0.040”(1mm)	3.7
Entrapped, %> 0.040”(1mm)	0.9
Air Voids/inch	9.7
Specific Surface, in^2/in^3	840
Spacing Factor, inches	0.006
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	21
Test Date	2/14/2011

Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023



Magnification: 10x
Description: Hardened air void system.

AIR VOID ANALYSIS

PROJECT:
Truck Transit Air Content Study

REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

ATTN: Maria Masten
DATE: February 15, 2011

AET PROJECT NO: 28-00182

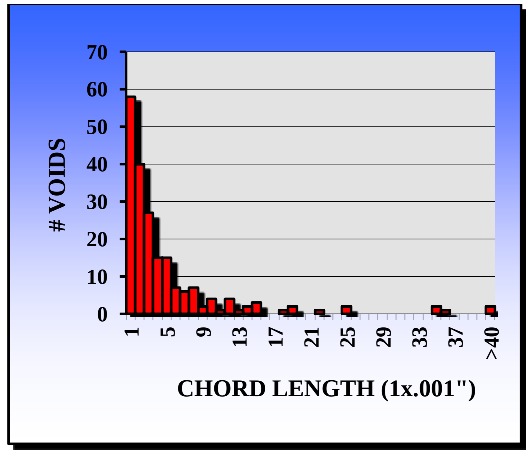
Sample Number: Task 3 Batch 18 (60 min.)
Conformance: The sample contains an air void system which appears consistent with current technology for freeze-thaw resistance.

Sample Data

Description: Hardened Concrete Cylinder
Dimensions: 102m (4") diameter by 205mm (8") long

Test Data:

Air Void Content %	5.2
Entrained, % < 0.040"(1mm)	4.4
Entrapped, %> 0.040"(1mm)	0.8
Air Voids/inch	9.7
Specific Surface, in^2/in^3	750
Spacing Factor, inches	0.006
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	21
Test Date	2/14/2011



Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023

Magnification: 10x
Description: Hardened air void system.

AIR VOID ANALYSIS

PROJECT:
Truck Transit Air Content Study

REPORTED TO:
Minnesota Department of Transportation
Mail Stop 645
Maplewood, MN 55109

ATTN: Maria Masten
DATE: February 15, 2011

AET PROJECT NO: 28-00182

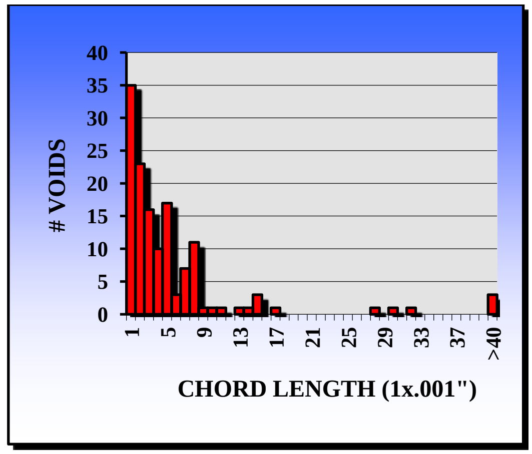
Sample Number: Task 3 Batch 18 (120 min.)

Conformance: The sample contains an air void system which appears consistent with current technology for freeze-thaw resistance.

Sample Data

Description: Hardened Concrete Cylinder

Dimensions: 102m (4") diameter by 205mm (8") long

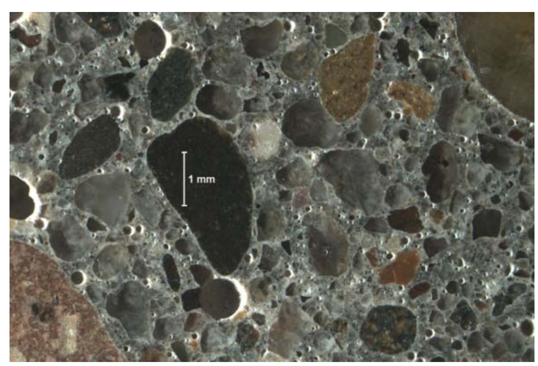


Test Data:

Air Void Content %	3.9
Entrained, % < 0.040"(1mm)	2.9
Entrapped, %> 0.040"(1mm)	1.0
Air Voids/inch	6.5
Specific Surface, in^2/in^3	660
Spacing Factor, inches	0.008
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	21
Test Date	2/14/2011

Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496, MN License #30023



Magnification: 10x
Description: Hardened air void system.

APPENDIX E: STATISTICAL ANALYSIS RAW DATA

Statistical Approach No. 1

Slump

Table E1. Task 1 - Slump

	60 min to 90 min	60 min to 120 min
P (t1= t2)	0.000944	0.132
P (t1 ≠ 120)	0.999056	0.868
Significance	Over 99% confident that change in delivery time will change slump	Change in delivery time does not significantly change slump
Mean Difference	0.882609	0.336957
95% Confidence Min Difference	0.402902	-0.10951
95% Confidence Max Difference	1.362315	0.783423

Note: Mixed at 90 Minutes, Explains increase.

Table E2. Task 2 - Slump

	60 min to 90 min	60 min to 120 min
P(t1=t2)	0.0663	0.0012
P (t1≠t2)	0.9337	0.9988
Significanc e	Slumps will be different with change in delivery time to a 90% Confidence Level	Slumps will be different with a change in delivery time to a 95% Confidence Level
Mean Difference	-1.00	-1.75

Note: Only 4 Pairs

Table E3. Task 3 - Slump

	60 min to 90 min	60 min to 120 min
P(t1=t2)	0.000153	0.000004
P(t1≠t2)	0.999847	0.999996
Significance	Over 99% Confident that change in delivery time will change slump	Over 99% Confident that change in delivery time will change slump
Average Difference	-0.821429	-1.660714286

Observation: Change in delivery time from 60 to 90 min and from 60 to 120 minutes does seem to have a significant event in all three tasks. This difference, however, does seem to be relatively small for slump in all cases (around 1 to 2 inches).

Air Content

Table E4. Task 1 - Air

	60 min to 90 min	60 min to 120 min
P (t1= t2)	0.008	0.201
P (t1 $\neq$ 120)	0.992	0.799
Significance	Over 99% confident that change in delivery time will change air	Change in delivery time does not significantly change air
Mean Difference	0.791	0.3522
95% Confidence LL Difference	0.234	-0.201
95% Confidence UL Difference	1.349	0.906

Note: Mixed at 90 Minutes – Explains increase

Table E5. Task 2 - Air

	60 min to 90 min	60 min to 120 min
P(t1=t2)	0.5813	0.4339
P (t1≠t2)	0.4187	0.5661
Significance	A change in delivery time will not significantly affect air	A change in delivery time will not significantly affect air
Average Difference	-0.175	-0.35

Note: Only 4 Pairs

Table E6. Task 3 - Air

	60 min to 90 min	60 min to 120 min
P(t1=t2)	0.000014	0.000774
P(t1≠t2)	0.999986	0.999226
Significance	Over 99% Confident that change in delivery time will change air	Over 99% Confident that change in delivery time will change air
Average Difference	-0.721429	-1.242857

Observation: Change in delivery time seems to significantly affect air content in Task 1, where re-mixing occurred at 90 minutes and air content was measured immediately after. With the mixing, the air is significantly higher than at 60 minutes.

There are only four pairs of data for Task 2 measurements, so it is hard to form a significant conclusion from the data. However, it is important to note that the average air content decreased at both 90 and 120 minutes from 60 minutes.

The results in Task 3 are significant, as in both cases, from 60 to 90 minutes and 60 to 120 minutes, the air content can be said to be different with over 99% confidence. However the average differences fall within a range of -0.5 and -1.5 %, showing that although this drop is consistent, it may not be detrimental to the concrete.

Table E7. Task 1 Hardened Air

P (0 min = 120 min)	0.49
P (0 min ≠ 120 min)	0.51
Significance	Change in delivery time does not drastically change hardened air content
Mean Difference	-0.55
95% Confidence LL Difference	-2.44
95% Confidence UL Difference	1.34

Note: 6 Measurements

Table E8. Task 3 Hardened Air

P (60 min = 120 min)	0.00076
P (60 min ≠ 120 min)	0.99924
Significance	Over 99% Confident that change in delivery time will change hardened air
Mean Difference	-1.24
95% Confidence LL Difference	-0.63
95% Confidence UL Difference	-1.86

Note: 14 Measurements

Observations: Change in hardened air content in Task 3is significant. Although it is 99% Confident that a change will occur, the magnitude of this drop is only around 1.25.

95% Confidence Intervals for a Change in DF/Slump/Air/Strength Corresponding to a Change in Delivery Time

The following plots help to visualize the how a change in delivery time can affect a particular property for a certain mix. This analysis was done by comparing the specific property at two delivery times for a ***single mix*** (two paired data sets, similar to paired T-Test). This gives a more meaningful representation of the effect of delivery time them by simply lumping the data from each delivery time into a data set and disregarding different mixes.

Slump

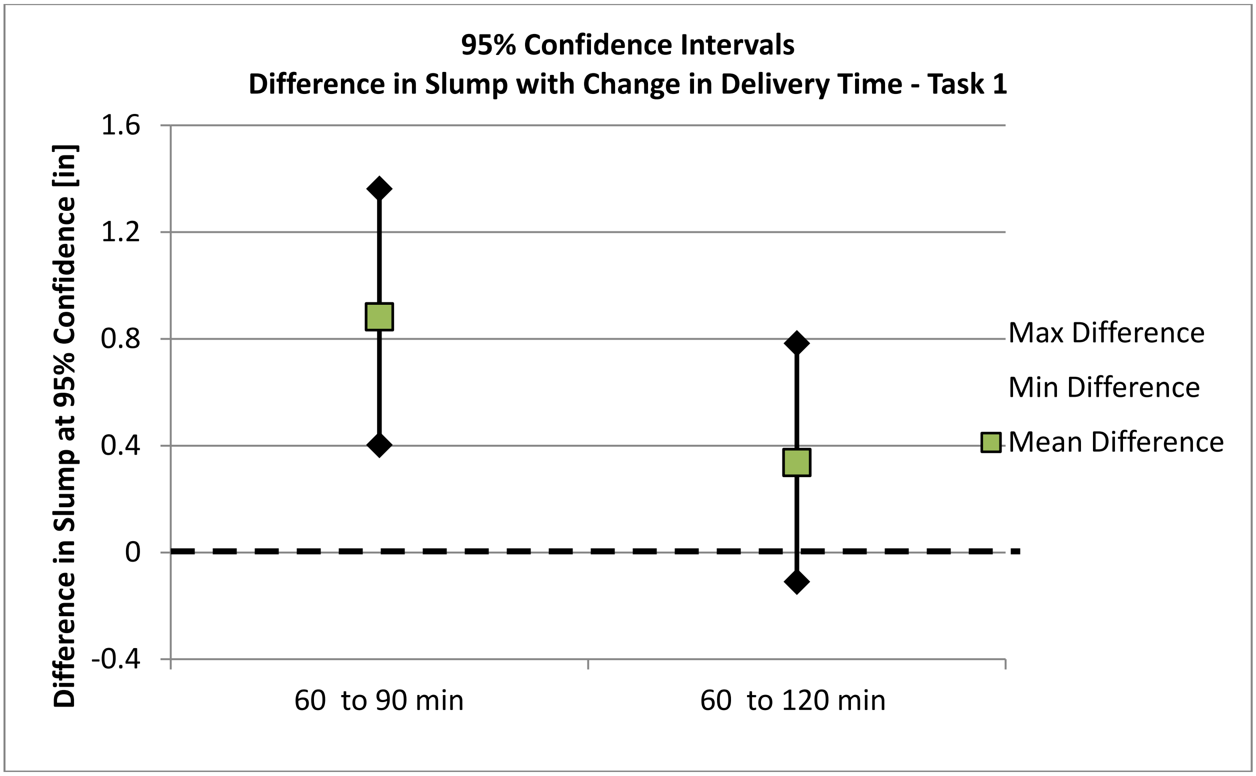


Figure E1. Difference in Slump with Change in Delivery Time - Task 1

Observation: There is less change in slump with a change in delivery time from 60 to 120 minutes than there is from 60 to 90 minutes. When changing delivery time from 60 to 120 minutes the slump can be expected to change anywhere between an increase of 0.8 inches and a decrease of 0.2 inches, with a 95% confidence. This plot illustrates how slump at 90 and 120 minutes usually increases from 60, which is probably due to the remixing at 90 minutes.

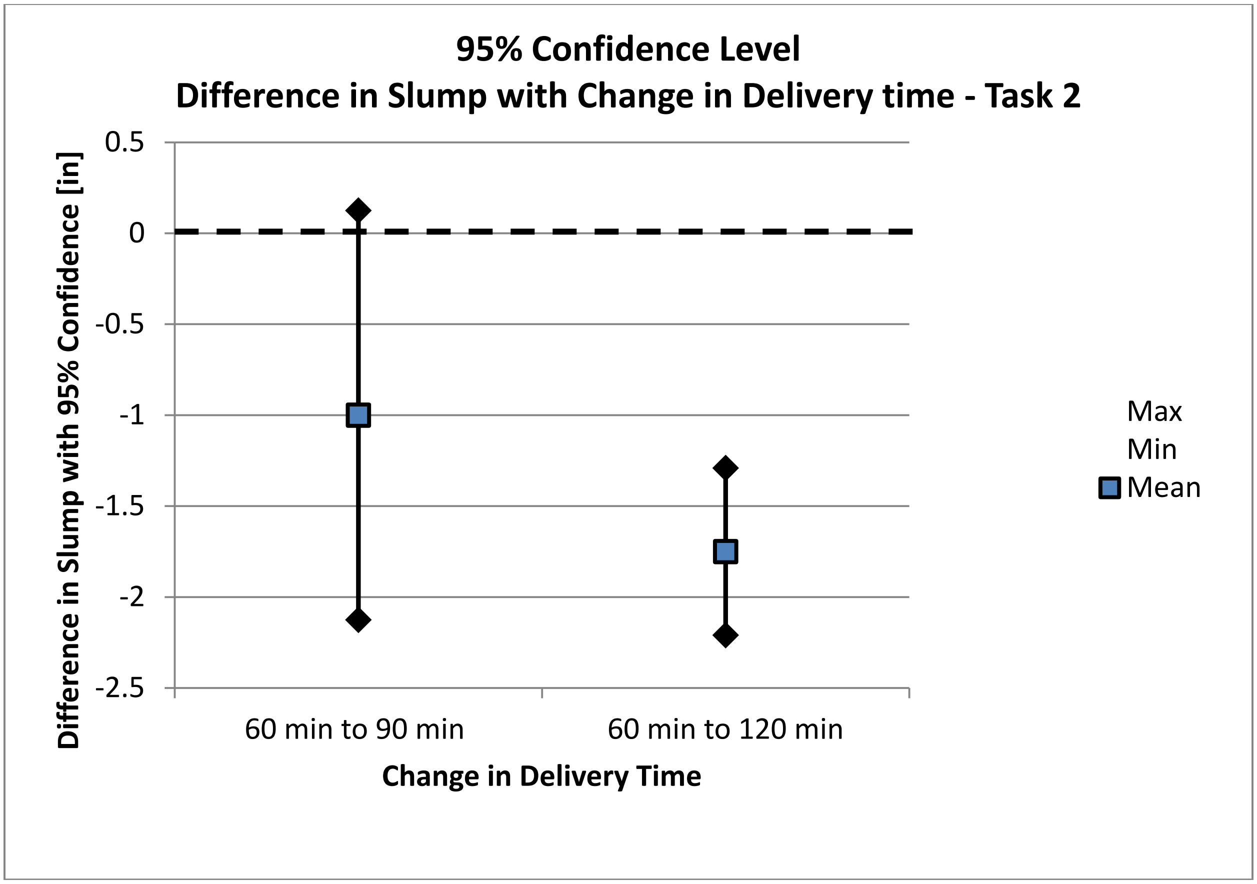


Figure E2. Difference in Slump with Change in Delivery Time - Task 2

Observation: Slump generally tends to decrease with a change in delivery time from 60 min to 90 or 120 minutes. Slump is more likely to decrease more with a change from 60 to 120 min versus a change from 60 to 90 minutes. With a change in delivery time from 60 to 120 minutes, slump can be expected to decrease over 2 inches with 95% confidence.

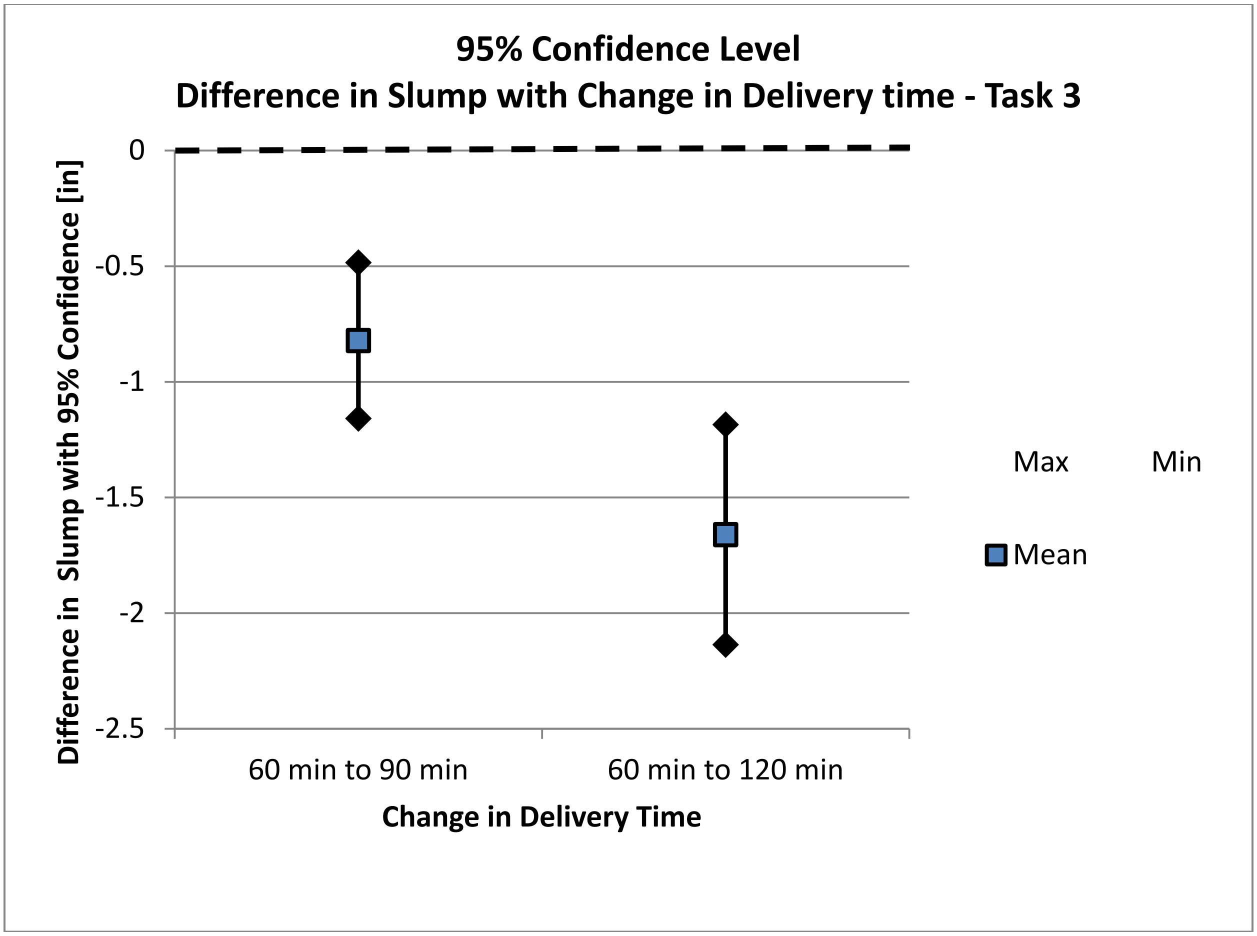


Figure E3. Difference in Slump with Change in Delivery Time - Task 3

Observation: Slump tends to decrease for a change in delivery time to both 9 0and 120 minutes. The decrease in slump from 60 to 120 minutes could be over 2 inches with 95% confidence, which may be significant.

Air Content

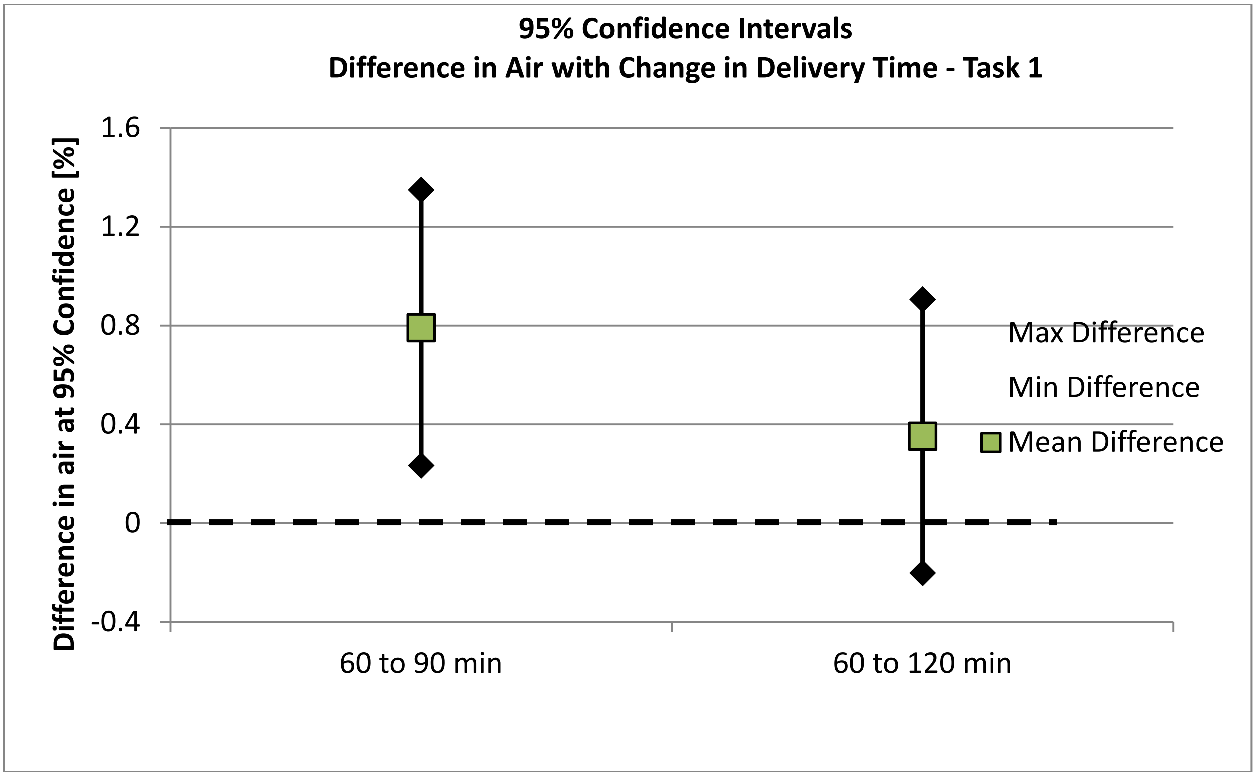


Figure E4. Difference in Air with Change in Delivery Time - Task 1

Observation: There is less change in air with a change in delivery time from 60 to 120 minutes than there is from 60 to 90 minutes. When changing delivery time from 60 to 120 minutes the slump can be expected to change anywhere between an increase of 1% and a decrease of 0.2%, with a 95% confidence. As with slump, air tends to increase at 90 and 120 minutes from 60 minutes, which is probably due to the remixing at 90 minutes.

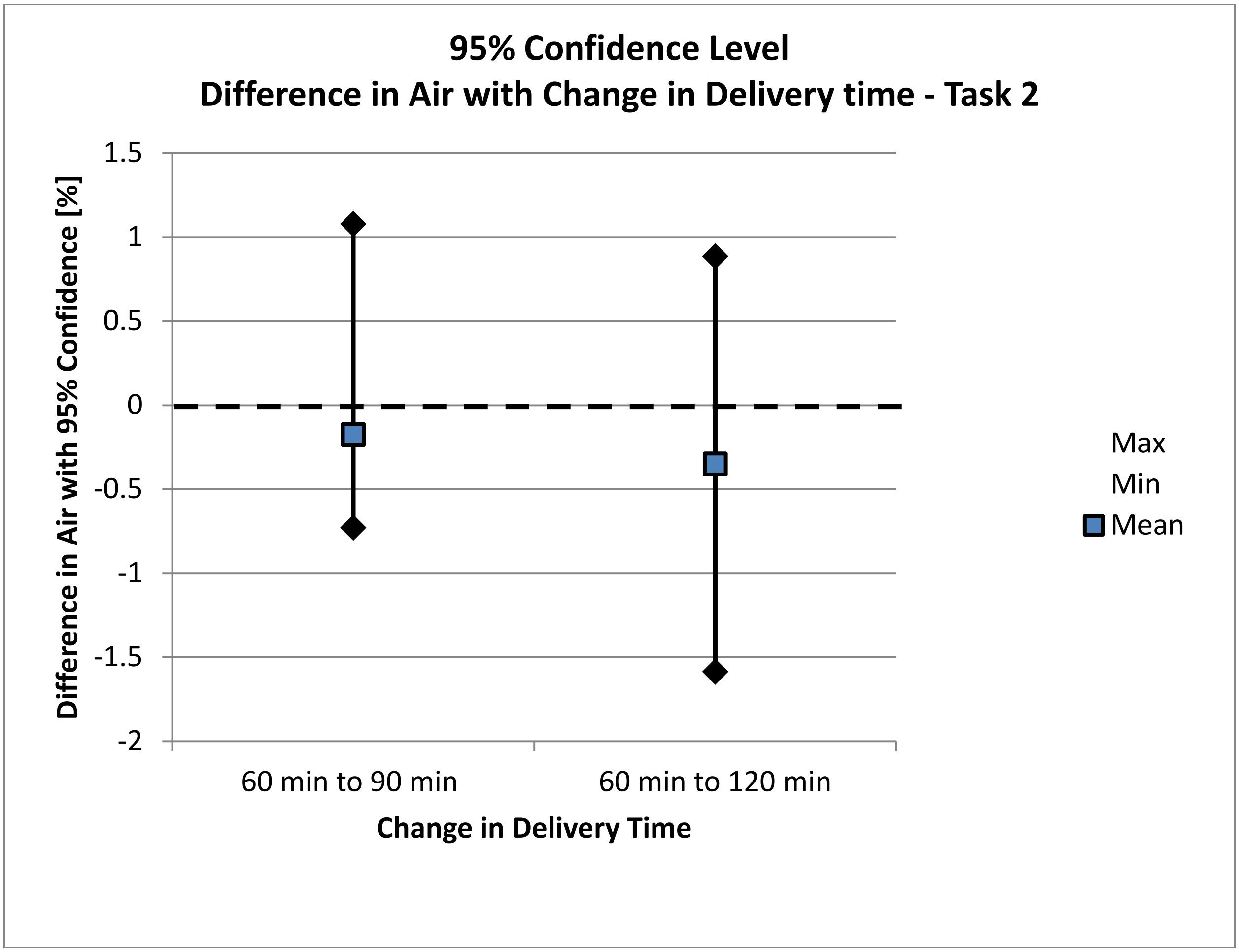


Figure E5. Difference in Air with Change in Delivery Time - Task 2

Observation: The average change in air for both 60 to 90 minutes and 60 to 120 minutes is very close to 0, suggesting that a change in delivery time may not have a significant effect on air in this task.

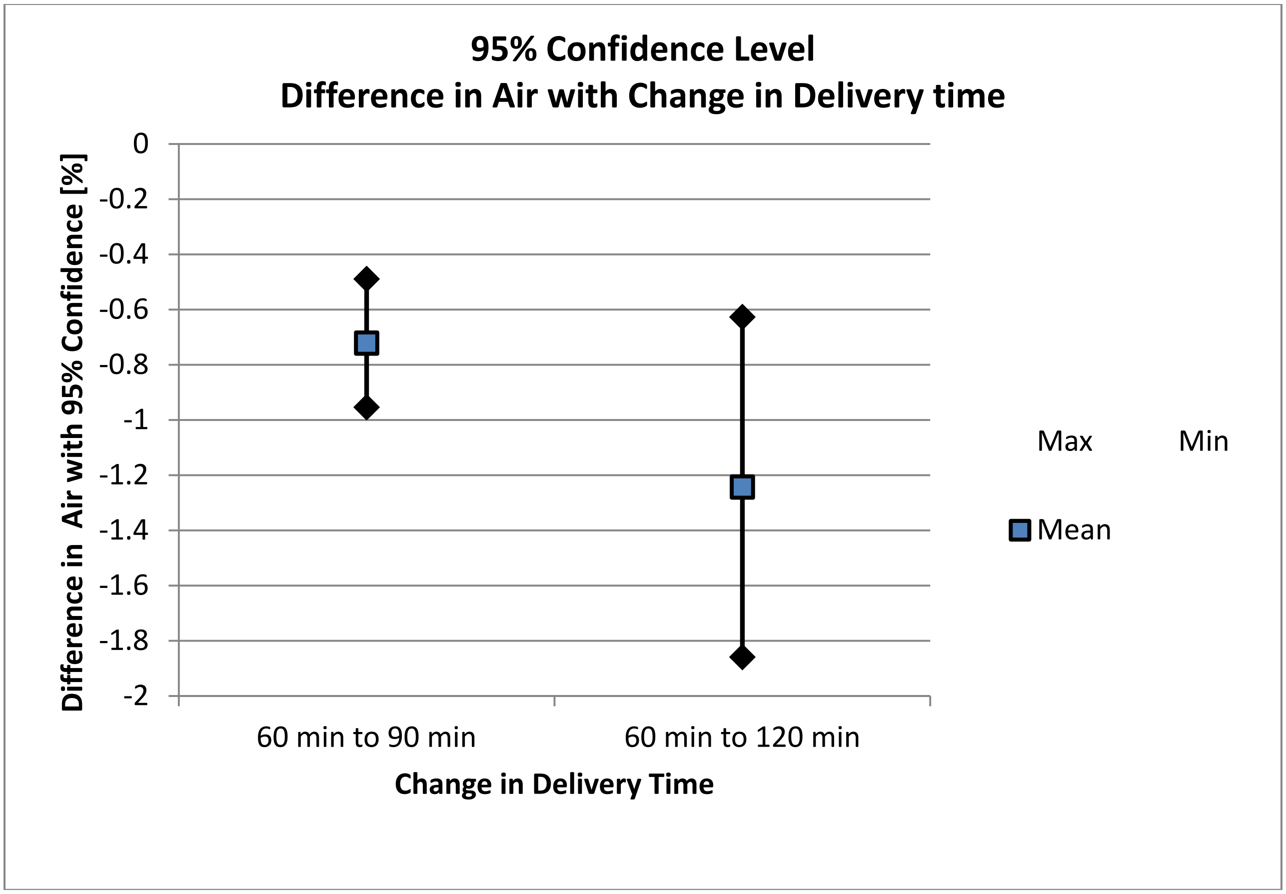


Figure E6. Difference in Air Slump with Change in Delivery Time

Observation: Air tends to decrease for a change in delivery time to both 9 0and 120 minutes. However, this decrease is minimal from 60 to 90 minutes, and the wide confidence level for 60 to 120 minutes suggests variability in the effect from mix to mix.

Compressive Strength

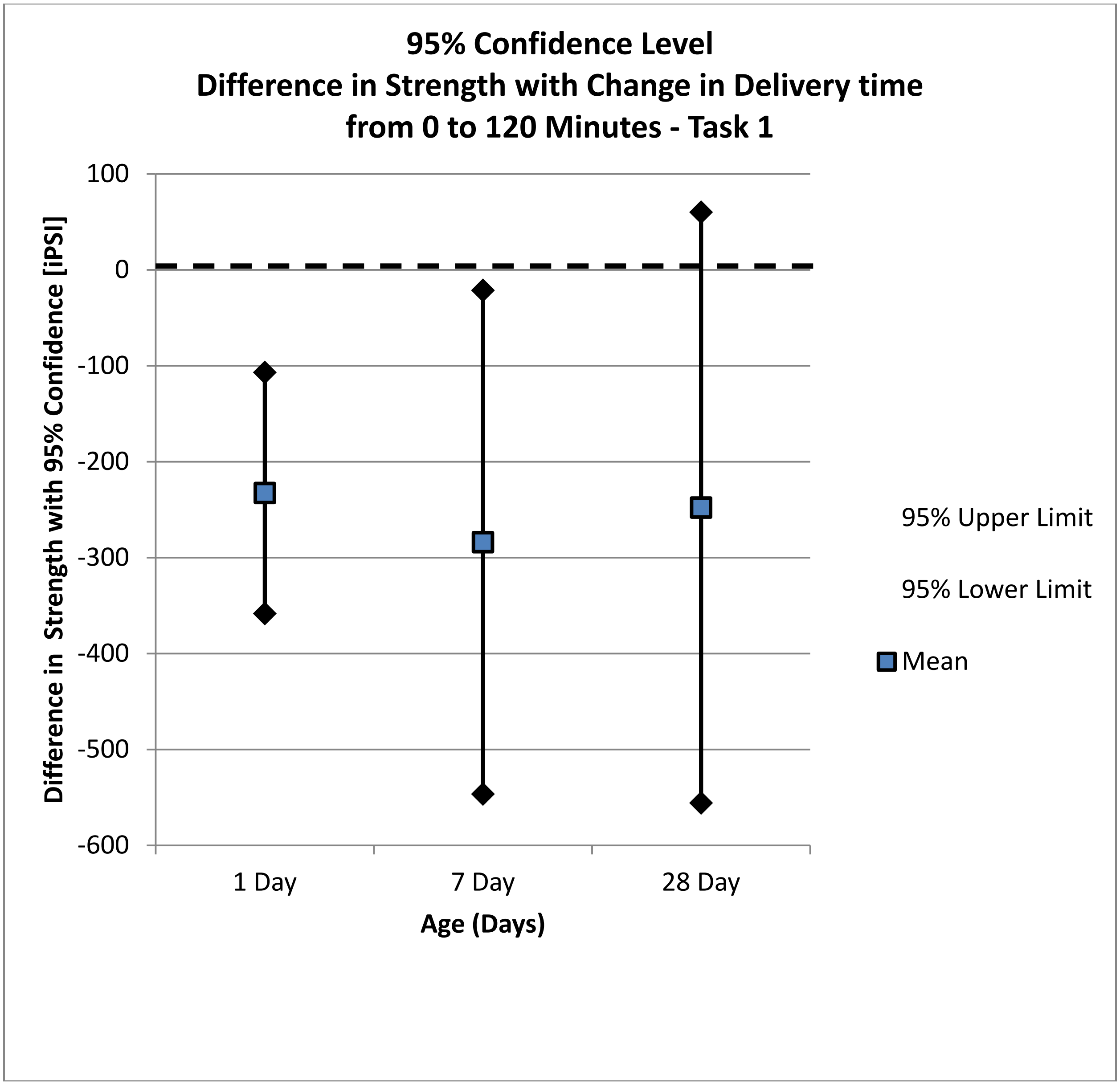


Figure E7. Difference in Strength with Change in Delivery Time from 0 to 12 Minutes Task 1

Observation: A change in delivery time from 0 to 120 minutes tends to decrease strength. However, the very large confidence intervals suggest that this is highly variable from mix to mix.

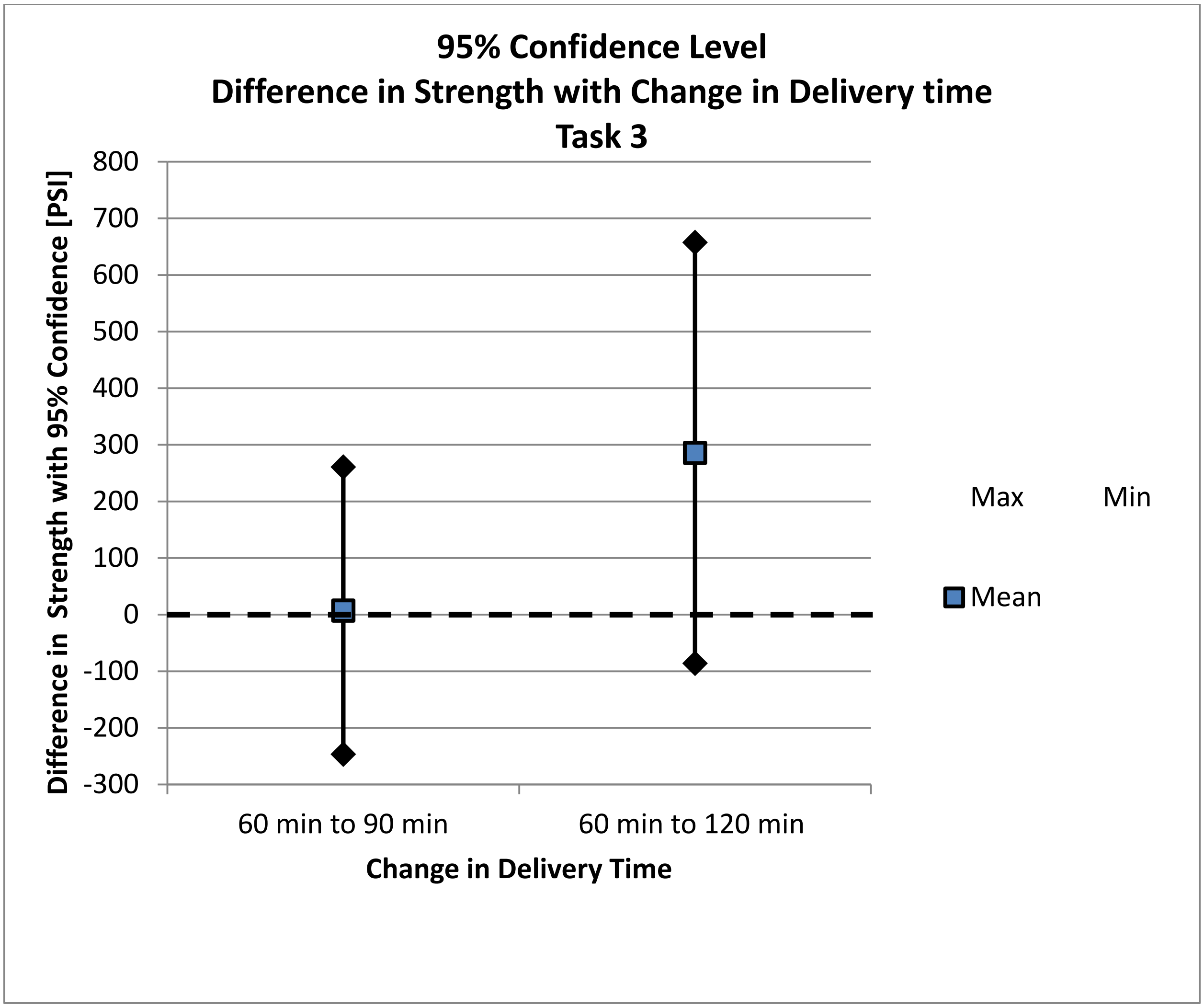


Figure E8. Difference in Strength with Change in Delivery Time - Task 3

Observation: The average difference between the compressive strength at a delivery of 60 min and 90 minutes is very close to zero, suggesting that the change in delivery time has little effect on strength, or its effect is not consistent across all mixes. Surprisingly, a change in delivery time from 60 to 120 minutes is actually more likely to increase strength than decrease it.

Durability Factor

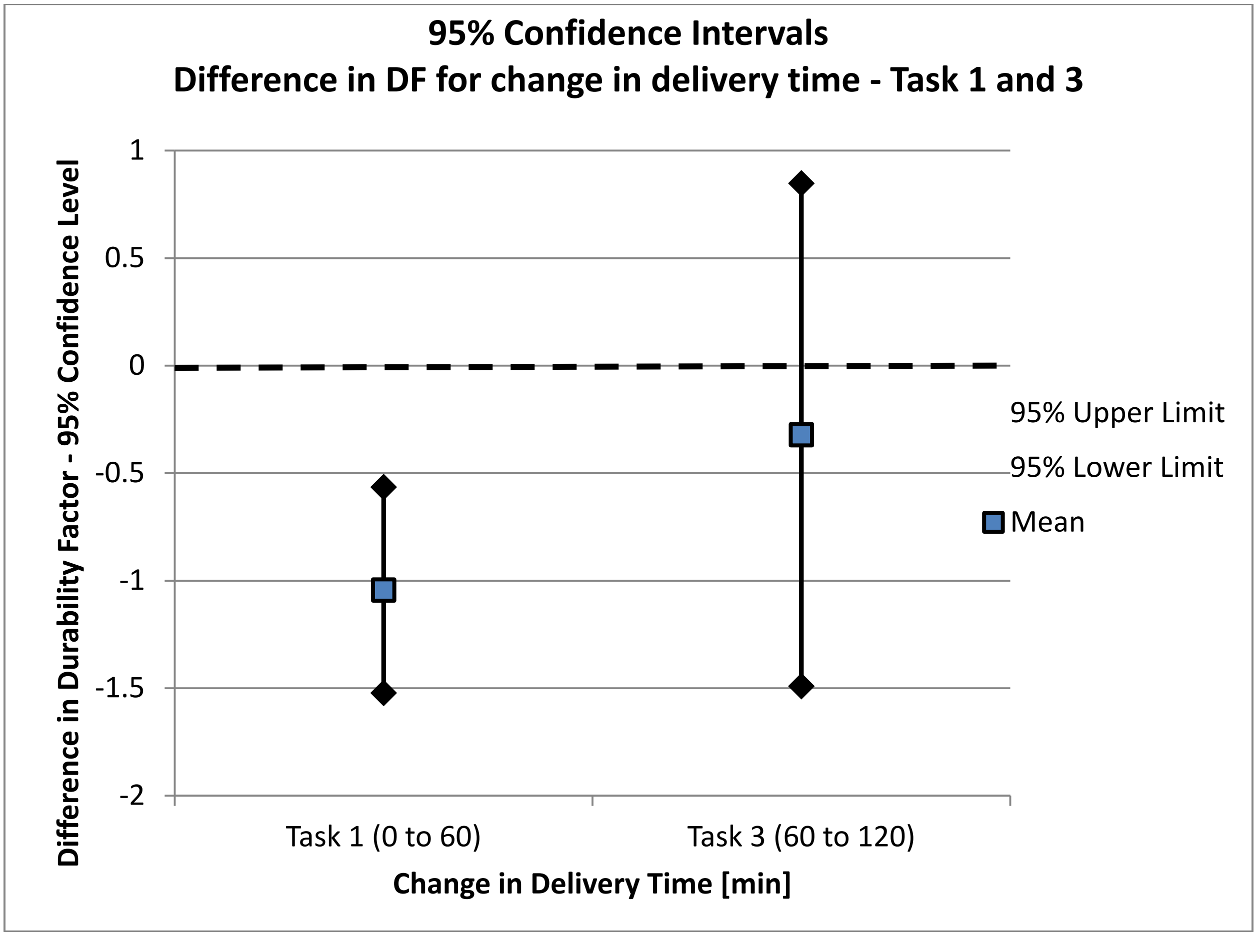


Figure E9. Difference in DF with Change in Delivery Time - Tasks 1 and 3

Observation: When changing delivery time from 60 to 120 minutes, the DF can be expected to change anywhere between an increase of 1.5 and a decrease of 1 with a 95% confidence level. The mean change in DF is relatively close to 0, suggesting there is little effect on durability when changing delivery time.

95% Confidence Intervals for Durability Factor (DF) at 0, 60, and 90 Minutes

The following plots help to illustrate the variability in durability factors between mixes at a given delivery time, and also give a visualization of the general increase (or decrease) in DF for a change in delivery time. (This analysis groups data from all different mixes as one data set, and therefore is a more general evaluation than the plots above).

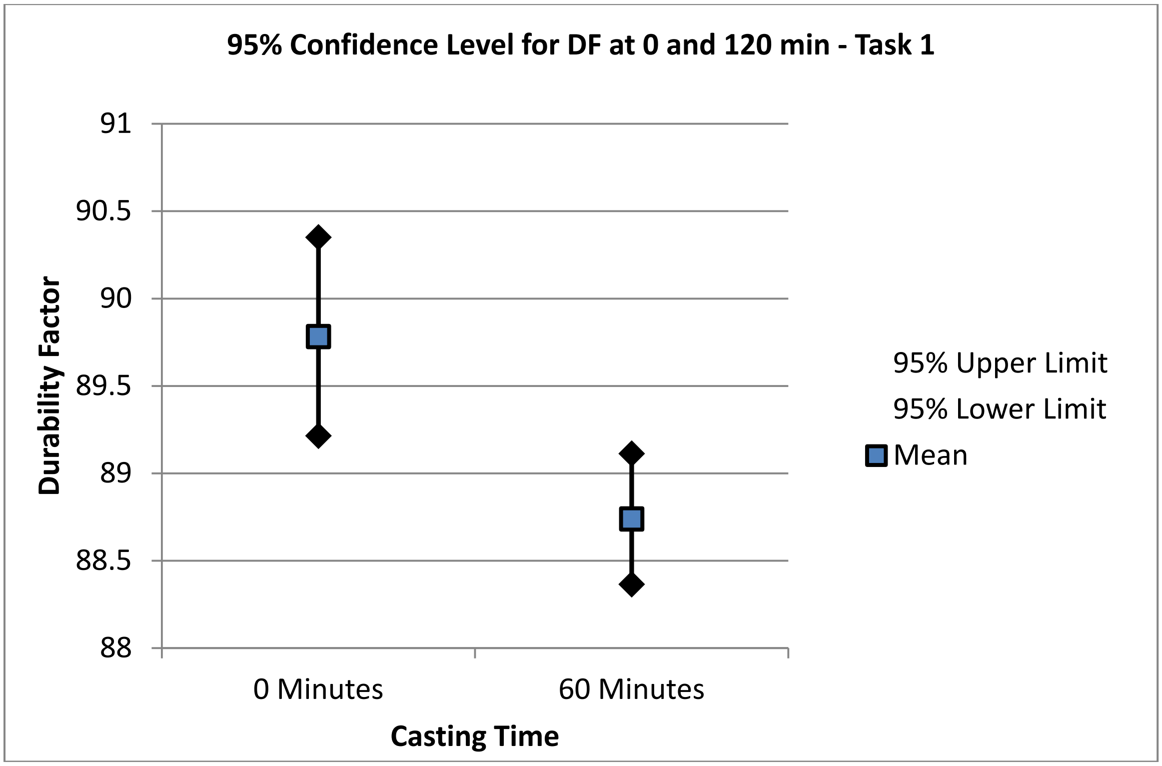


Figure E10. 95% Confidence Level for DF at 0 and 120 min - Task 1

Observation: DF is lower and less variable at 60 minutes than 0 minutes.

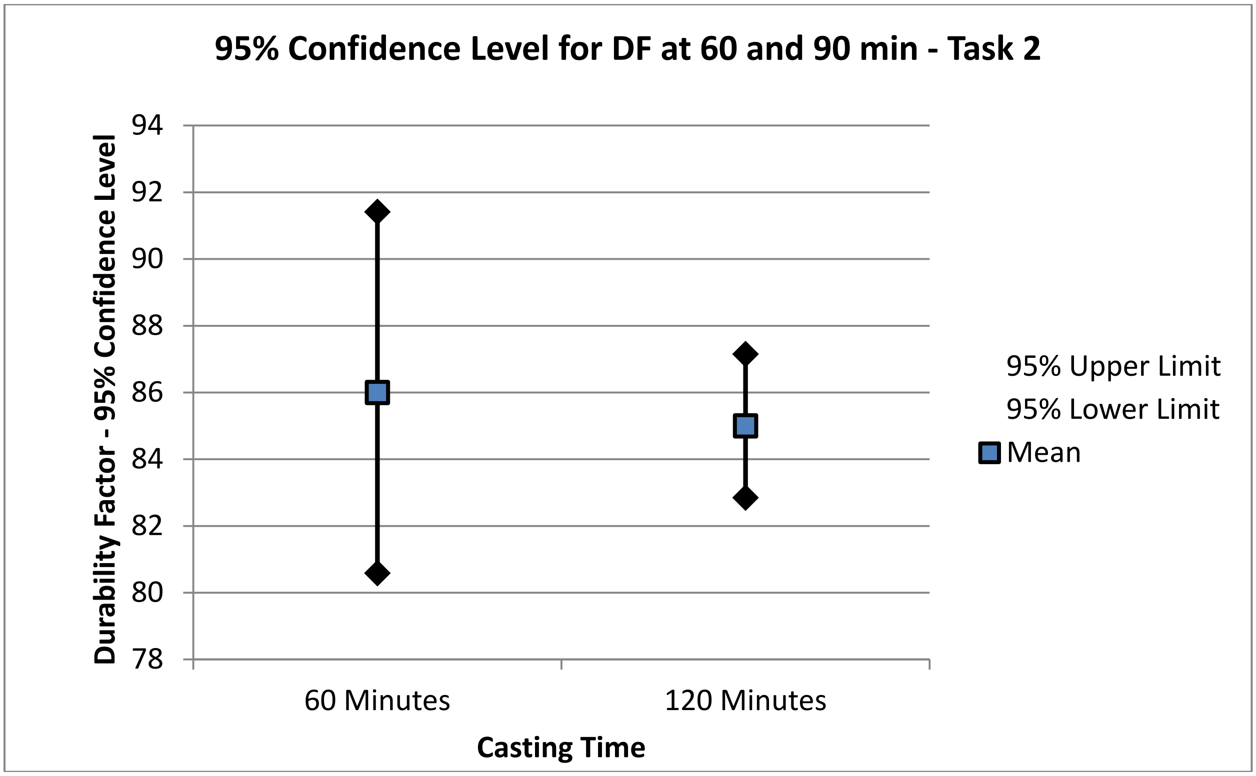


Figure E11. 95% Confidence Level for DF at 60 and 90 min - Task 2

Observation: DF is only slightly lower and much less variable at 120 minutes than 60 minutes.

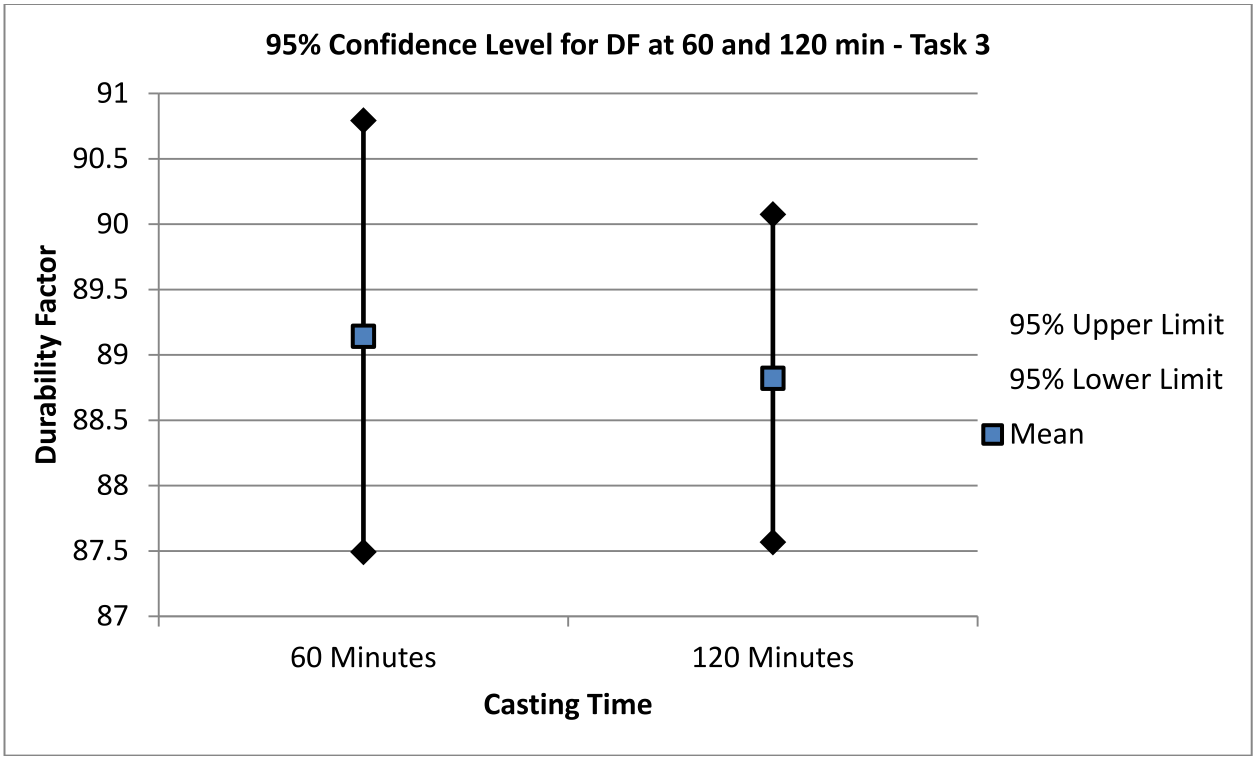


Figure E12. 95% Confidence Level for DF at 60 and 120 min - Task 3

Observation: DF is slightly lower and less variable at 120 minutes than 60 minutes.

Statistical Approach No. 2

Table E14 summarizes the effects of changing fly ash type, changing air entrainer type and changing cement/retarding WR combination on the test results. This table shows:

- The general effect of changing fly ash type from 1 to 2 resulted in increased 28-day compressive strengths for both transit times, but especially when transit time is low (t=0). The impact of fly ash type on durability factor and dilation was negligible.
- The general effects of changing air-entraining type on 28-day compressive strength, durability factor and dilation were not statistically significant.
- The general effects of changing cement-retarding water-reducer type combinations on 28-day compressive strength, durability factor and dilation were not statistically significant.
- The two-way and three-way interaction effects of the three main variables (fly ash type, air-entrainer type, and cement-retarding water-reducer type) were all relatively small and appear to be statistically insignificant (although there are not enough data runs to provide a standard error of estimate to be certain).

Table E14. Average effects of fly ash type, AE type and cement/RWR combination on test results based on Batches 1 – 8 (standard deviations in parentheses)

	FA1 to FA2	**AE1 to AE2**	**Cem2/RWR 2 to Cem1/RWR 3**	**FA x AE**	**FA x Cem/RWR**	**AE x Cem/RWR**	**3-way Interaction**
f'c (28-day), psi							
t=0	633 (386)	337 (389)	-18 (245)	263	-7.5	-42.5	-207.5
t=120	195 (396)	230 (398)	-160 (370)	185	135	140	255
Δ (t=0 to t=120)	-438 (566)	-108 (581)	-143 (597)	-78	142.5	182.5	462.5
DF							
t=0	0.25 (1.9)	-0.75 (3.6)	-0.75 (3.6)	-0.75	0.75	2.75	-1.25
t=120	0 (1.4)	0 (2.2)	1 (2.2)	-0.5	-0.5	-1.5	1
Δ (t=0 to t=120)	0.25 (1.5)	-0.75 (2.1)	0.25 (1.5)	1.25	0.25	1.25	-0.25
Dilation, %							
t=0	0 (0)	0 (0)	0 (0)	0	0	0	0
t=120	-0.0025 (0.005)	-0.0025 (0.005)	-0.0025 (0.005)	-0.0025	0.0025	0.0025	0.0025
Δ (t=0 to t=120)	-0.0025 (0.005)	-0.0025 (0.005)	-0.0025 (0.005)	-0.0025	-0.0025	-0.0025	-0.0025

Table E15 summarizes the effects of changing fly ash type and various combinations of chemical admixtures on the test results. This table shows:

- The general effect of changing fly ash type from 1 to 2 resulted in increased 28-day compressive strengths for both transit times, but especially when transit time is low (t=0). The impact of fly ash type on durability factor and dilation was negligible.
- The general effects of changing from admixture combinations from 1 to 2 through 6 on concrete durability (DF or dilation) were negligible.
- The effects on concrete strength of changing from admixture combination 1 to combinations 2 through 6 varied greatly. Combination 2 resulted in slightly higher strengths (295 to 370 psi) at both transit times. Combination 3 produced significantly higher strength for low transit times and extremely significant reductions in strength (>1300 psi) for long transit times. Combination 4 had little impact on strength for low transit times, but produced significantly lower strength (855 psi lower) for long transit time. Combination 5 produced lower strengths for both transit times (results of marginal significance), while combination 6 produced much lower strengths for both transit times (1335 psi lower for t = 0 and 880 psi lower for t = 120).

Table E15. Average effects of fly ash type and various chemical admixture combinations on test results based on Batches 5 – 12, 15, 16, 18, 19 (standard deviations in parentheses)

	FA1 to FA2	Comb 1 to Comb 2	Comb 1 to Comb 3	Comb 1 to Comb 4	Comb 1 to Comb 5	Comb 1 to Comb 6
f'c (28-day), psi						
t=0	537 (337)	295 (78)	555 (64)	45 (361)	-590 (354)	-1335 (148)
t=120	387 (360)	370 (622)	-1345 (163)	-855 (361)	-530 (311)	-880 (651)
Δ (t=0 to t=120)	-150 (516)	75 (544)	-1900 (226)	-900 (721)	60 (42)	455 (799)
DF						
t=0	-0.2 (1.8)	2.0 (2.8)	0 (2.8)	-0.5 (3.5)	1.0 (2.1)	0.0 (1.4)
t=120	-0.2 (0.8)	1.5 (0.7)	0 (1.4)	0.5 (0.7)	0.5 (0.7)	0.0 (1.4)
Δ (t=0 to t=120)	0.0 (1.7)	-0.5 (2.1)	0 (1.4)	1.0 (2.8)	-0.5 (2.1)	0 (0)
Dilation, %						
t=0	0	0	0	0	0	0
t=120	0	0	0	0	0	0
Δ (t=0 to t=120)	0	0	0	0	0	0

Notes:

1) Combination 1 is AE1, RWR3, no MRWR
2) Combination 2 is AE2, RWR3, no MRWR
3) Combination 3 is AE3, RWR4, no MRWR
4) Combination 4 is AE1, RWR1, MRWR1
5) Combination 5 is AE4, RWR6, MRWR2
6) Combination 6 is AE5, RWR7, MRWR3

Table E16 summarizes the effects of changing cement type (from 1 to 3) and fly ash type (from 1 to 2) while holding all other factors constant. This table shows:

- The effects of cement type and fly ash type on concrete durability, as indicated by durability factor or dilation, were insignificant for this data set.
- Changing cement type from 1 to 3 had no significant effect on concrete strength for either transit time.
- Changing fly ash from type 1 to type 2 increased concrete strength for both transit times by 695 to 780 psi. Given the variability of the test results, these results are only mildly significant, but they are consistent with the effects of fly ash seen in other data subsets for Task 1.
- The two-way interaction of cement and fly ash on concrete strength is variable and probably not statistically significant for this data set (insufficient data is available for accurately assessing statistical significance).

Table E16. Average effects of fly ash types 1 and 2 and cement types 1 and 3 based on test results for Batches 13 – 16 (standard deviations in parentheses)

	Cem 1 to Cem 3	**FA 1 to FA 2**	**Two-Way Interaction**
f'c (28-day), psi			
t=0	265 (530)	695 (530)	375
t=120	-170 (636)	780 (636)	-450
Δ (t=0 to t=120)	-435 (1167)	85 (1167)	-825
DF			
t=0	-1 (1.4)	0 (1.4)	-1
t=120	-1.5 (0.7)	-0.5 (0.7)	0.5
Δ (t=0 to t=120)	-0.5 (2.1)	-0.5 (2.1)	1.5
Dilation, %			
t=0	0	0	0
t=120	0	0	0
Δ (t=0 to t=120)	0	0	0

Table E17 summarizes the effects of changing fly ash type (from 1 to 3) and admixture combination (from 6 to 7) while holding all other factors constant. This table shows:

- The effects of fly ash type and admixture combination on concrete durability, as indicated by durability factor or dilation, were insignificant for this data set.
- Changing fly ash type from 1 to 3 resulted in greatly increased strength for both transit times. Given the lack of replicate data, it is impossible to say that the increase at t = 120 mins is statistically significant, but the increase for t = 0 (1480 psi) is highly significant.
- Changing the admixture combination from 6 to 7 appeared to increase 28-day compressive strength for 0 transit time by an average of 720 psi (although this increase is not statistically significant for this data set). No apparent or significant increase in compressive strength was observed for the longer transit time (t = 120 mins).
- The two-way interaction of fly ash and admixture combination on concrete strength appears to be worthy of consideration (especially for t = 120 mins), but it is impossible to assess the statistical significance of these values from the limited data available.

Table E17. Average effects of fly ash types 1 and 3 and admixture combinations 6 and 7 based on test results for Batches 17, 18, 20 and 21 (standard deviations in parentheses)

	FA1 to FA 3	**Admix Comb 6 to Admix Comb 7**	**Two-Way Interaction**
f'c (28-day), psi			
t=0	1480 (594)	720 (594)	420
t=120	740 (863)	-60 (863)	610
Δ (t=0 to t=120)	-740 (269)	-780 (269)	190
DF			
t=0	1 (1.4)	-1 (1.41)	-1
t=120	0.5 (0.71)	-0.5 (0.71)	-0.5
Δ (t=0 to t=120)	-0.5 (0.71)	0.5 (0.71)	0.5
Dilation, %			
t=0	0	0	0
t=120	0	0	0
Δ (t=0 to t=120)	0	0	0

Note: Admixture Combination 1 = AE5, MRWR3 and RWR7; Admixture Combination 2 = AE3, no MRWR, RWR5

Table E18 summarizes the effects of changing cementitious content (from 578 pcy to 655 pcy) and SCM type/replacement level (from 20 percent fly ash to 35 percent slag cement) while holding all other factors constant. This table shows:

- The use of higher cementitious content resulted in higher slump values for both transit times (average increase of 1.625 inches, which appears to be statistically significant). The effect of changing SCM type and replacement level appears to have slightly increased the slump for 60 minutes of transit time, while reducing slump very slightly for 120 minutes of transit time; the size of these effects is not significant. There also appears to be no significant two-way interaction effect on slump.
- The use of more cementitious material appeared to slightly increase plastic air content at 120 minutes of transit time while having an insignificant effect on plastic air content at 60 minutes of transit time. Changing SCM type and replacement level appeared to increase plastic air content for both transit times. The two-way interaction effect on plastic air is small and is probably not significant.
- The use of more cementitious material appeared to decrease hardened air content at 60 minutes of transit time while having an insignificant effect on hardened air content at 120 minutes of transit time. Changing SCM type and replacement level appeared to increase hardened air content at 60 minutes of transit time while having an insignificant effect on hardened air content at 120 minutes of transit time. The two-way interaction effect on hardened air is small and is probably not significant.
- Changes in cementitious content and/or SCM type/replacement level had only small effects on 28-day compressive strength – all statistically insignificant if one assumes a typical coefficient of variation for compressive strength of 10 percent or 500 psi.
- Changes in cementitious content and/or SCM type/replacement level had small (probably insignificant) effects on measures of concrete durability. It should be noted that freeze-thaw testing was accomplished on only 3 of the 4 mixtures, which limited the ability to determine the effects on durability.

Table E18. Average effects of cementitious content and SCM type/replacement level on test results for Task 2 (standard deviations in parentheses)

	Cementitious Content (578 pcy to 655 pcy)	20% Fly Ash to 35% Slag Cement	Two-Way Interaction
Slump, in			
t = 60	1.625 (0.53)	0.375 (0.53)	-0.375
t = 120	1.625 (0.53)	-0.125 (0.53)	-0.375
Δ (t = 60 to t = 120)	0 (0)	-0.5 (0)	0
Plastic Air Content, %			
t = 60	0.05 (0.78)	1.55 (0.78)	0.55
t = 120	0.65 (0.35)	0.65 (0.35)	-0.25
Δ (t = 60 to t = 120)	0.6 (1.13)	-0.9 (1.13)	-0.8
Hardened Air Content,%			
t = 60	-1.1 (0.71)	1.2 (0.71)	-0.5
t = 120	0.4 (1.27)	0.4 (1.27)	-0.9
Δ (t = 60 to t = 120)	1.5 (0.57)	-0.8 (0.57)	-0.4
f'c (28-day), psi			
t = 60	205 (64)	155 (64)	-45
t = 120	-135 (799)	395 (799)	565
Δ (t = 60 to t = 120)	-340 (863)	240 (863)	610
DF			
t = 60	1.5*	-3.75*	n/a
t = 120	-0.75*	-0.75*	n/a
Δ (t = 60 to t = 120)	-2.25*	3*	n/a
Dilation, %			
t = 60	-0.0025*	0.005*	n/a
t = 120	0*	0*	n/a
Δ (t = 60 to t = 120)	0.0025*	-0.005*	n/a

*std dev cannot be computed because freeze-thaw tests were not performed for one mixture (655 pcy with slag)

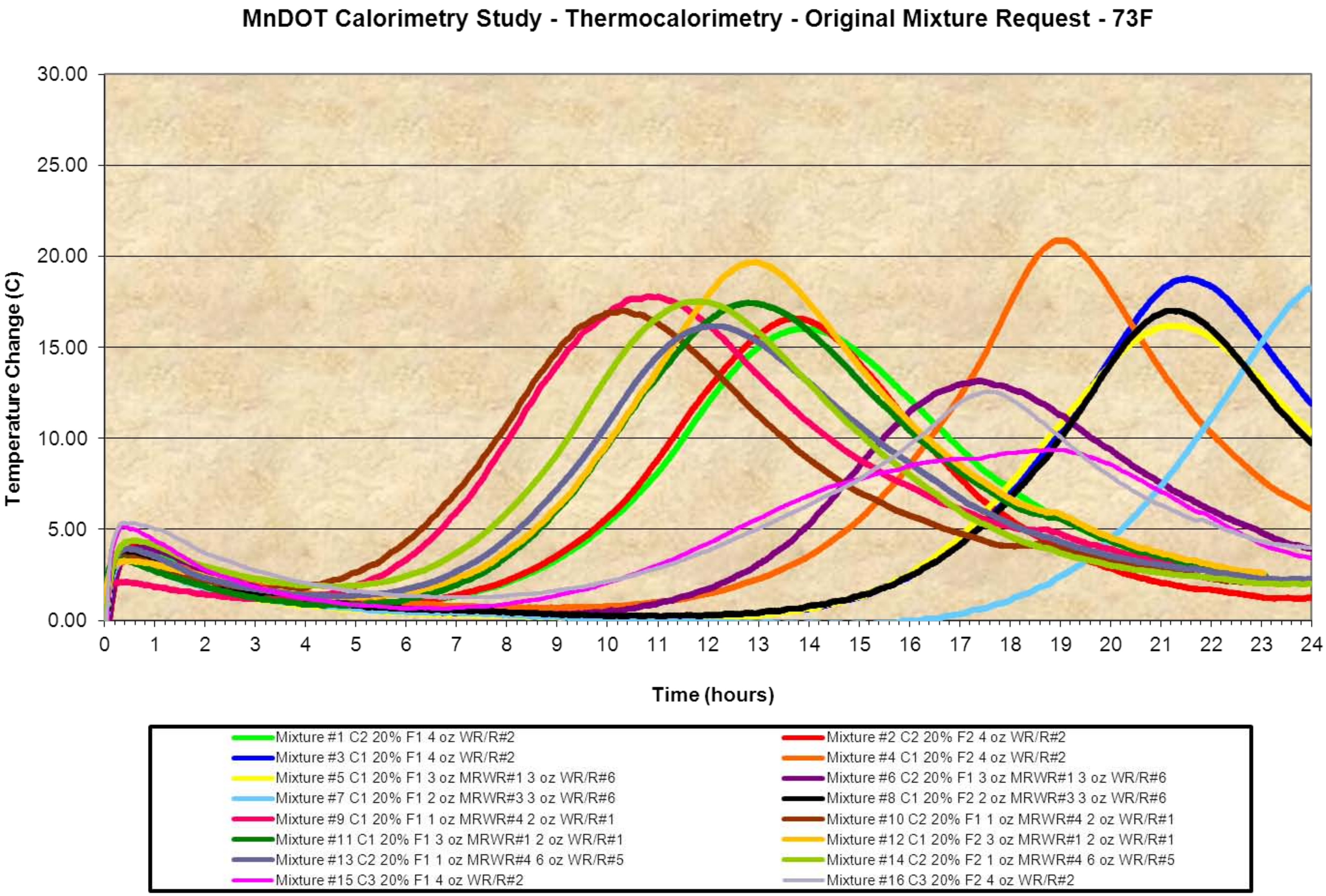
Table E19 summarizes the effects of changing the mixture design from 3A32 to 3Y43 while holding all other factors constant. This table shows:

- 3Y43 mixtures had slump values that were 1.68 inches and 1.64 inches higher than the corresponding 3A32 mixtures at transit times of 60 and 120 minutes, respectively. The average difference in slump at 60 and 120 minutes was about the same for both mixture designs.
- There was no significant difference in plastic or hardened air content at either transit time as a result of using 3Y43 mix designs rather than 3A32 mixtures.
- There was no significant difference in 28-day compressive strength either transit time as a result of using 3Y43 mix designs rather than 3A32 mixtures.
- There was no significant difference in durability factor or freeze-thaw dilation at either transit time as a result of using 3Y43 mix designs rather than 3A32 mixtures.

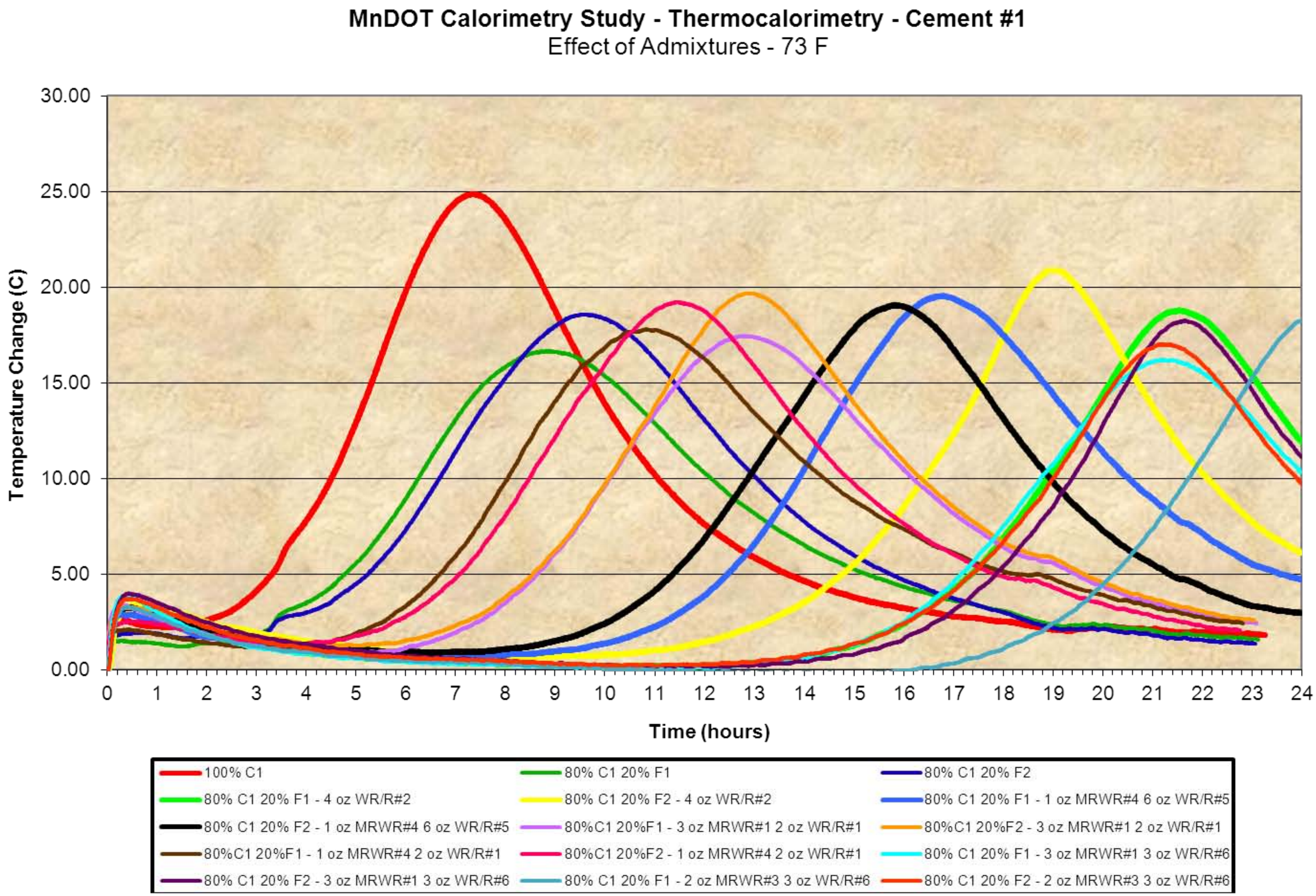
Table E19. Average effects of changing mix design from 3A32 to 3Y43 on Task 3 test results (standard deviations in parentheses)

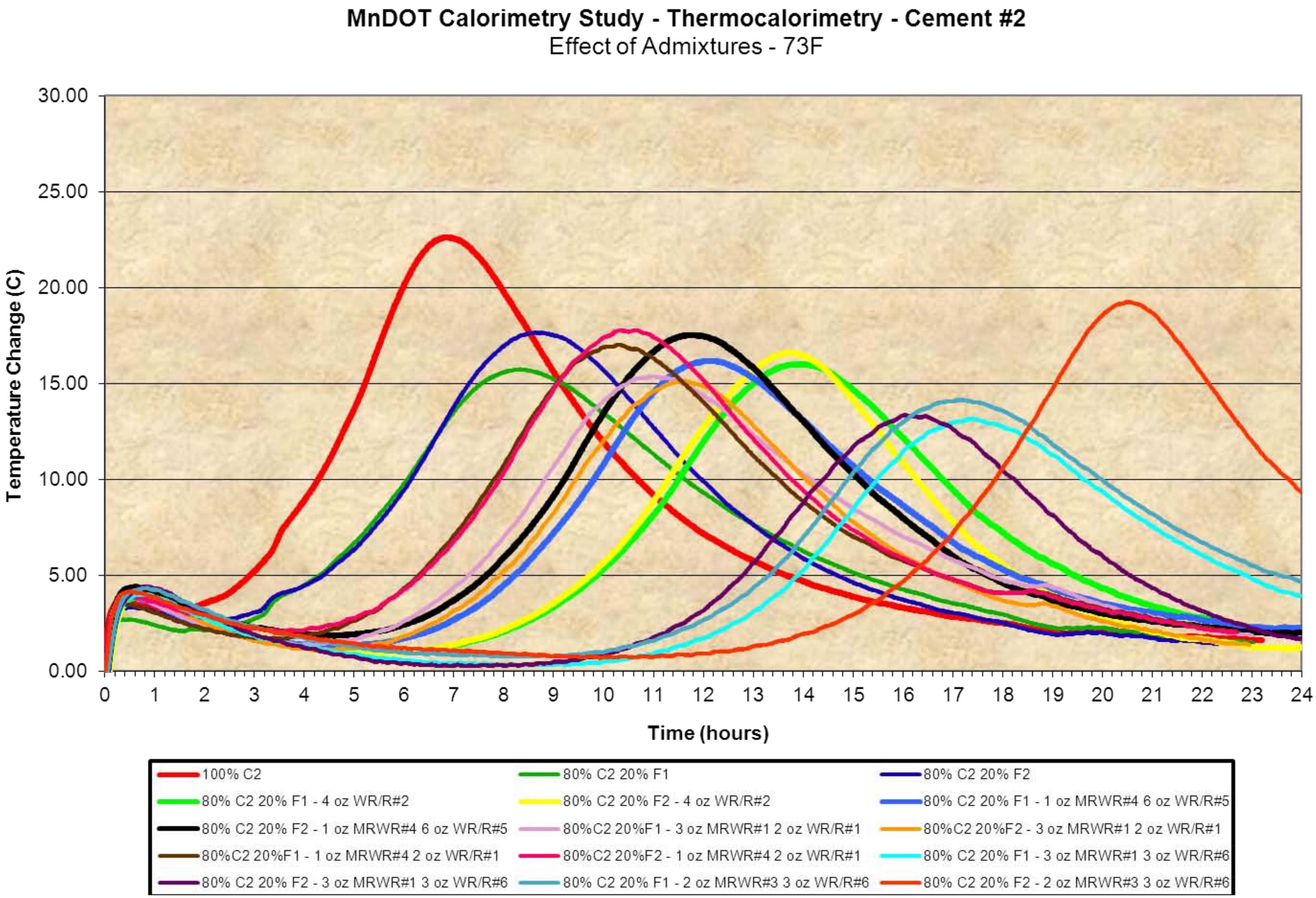
	Mixture Design (3A32 to 3Y43)
Slump, in	
t = 60	1.68 (2.92)
t = 120	1.64 (3.32)
Δ (t = 60 to t = 120)	-0.04 (0.96)
Plastic Air Content, %	
t = 60	-0.06 (0.89)
t = 120	0.03 (1.93)
Δ (t = 60 to t = 120)	0.09 (1.22)
Hardened Air Content,%	
t = 60	-0.17 (1.94)
t = 120	-0.09 (1.38)
Δ (t = 60 to t = 120)	0.09 (1.71)
f’c (28-day), psi	
t = 60	106 (822)
t = 120	229 (1150)
Δ (t = 60 to t = 120)	123 (654)
DF	
t = 60	-0.6 (1.74)
t = 120	0.4 (1.90)
Δ (t = 60 to t = 120)	1.0 (2.25)
Dilation, %	
t = 60	0 (0)
t = 120	-0.0007 (0.0019)
Δ (t = 60 to t = 120)	-0.0007 (0.0019)

APPENDIX F: THERMO CALORIMETRY GRAPHS

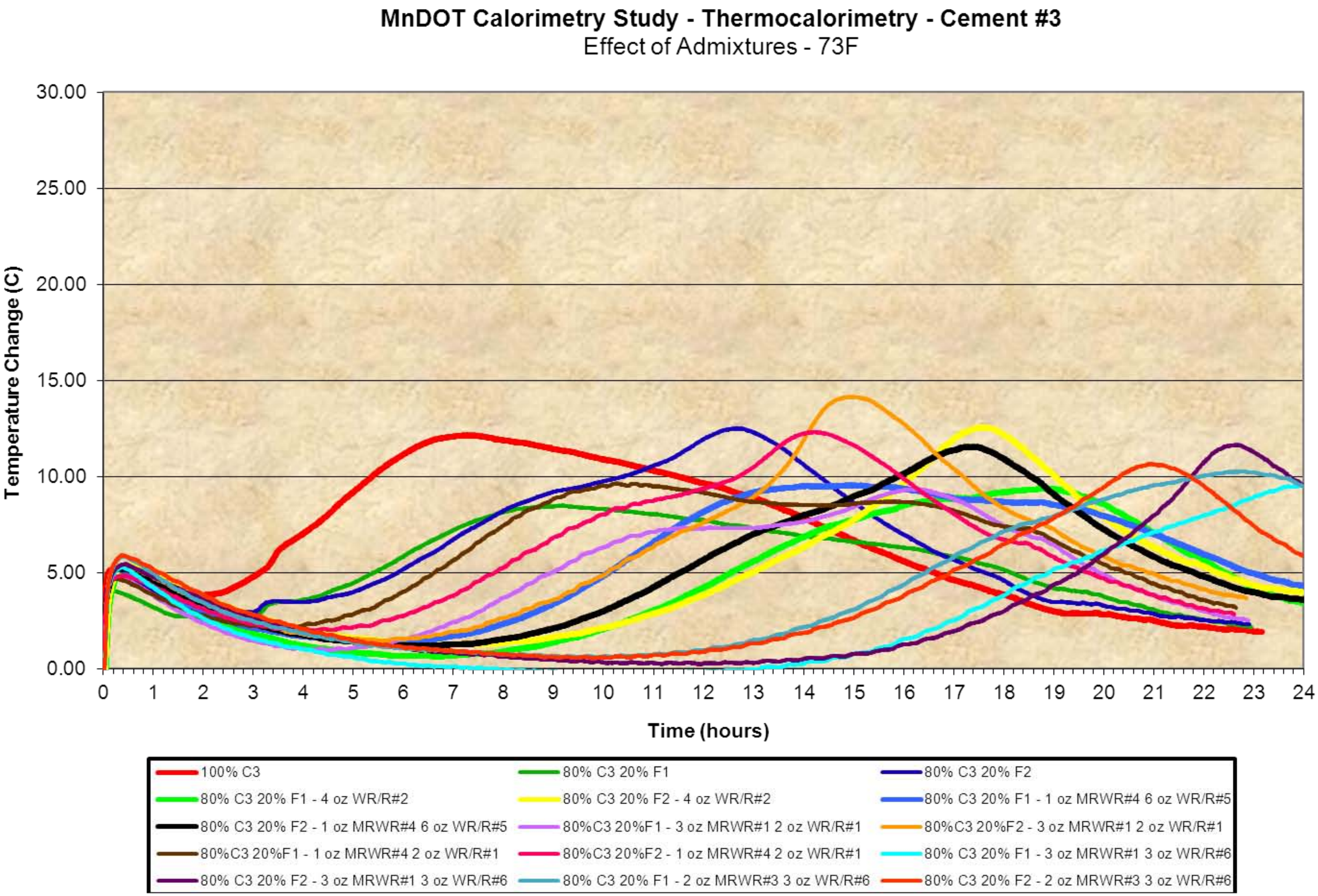


MnDOT Calorimetry Study - Thermocalorimetry - Original Mixture Request - 73F
Temperature Change (C)
30.00
25.00
20.00
15.00
10.00
5.00
0.00
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Time (hours)
Mixture #1 C2 20% F1 4 oz WR/R#2
Mixture #2 C2 20% F2 4 oz WR/R#2
Mixture #3 C1 20% F1 4 oz WR/R#2
Mixture #4 C1 20% F2 4 oz WR/R#2
Mixture #5 C1 20% F1 3 oz MRWR#1 3 oz WR/R#6
Mixture #6 C2 20% F1 3 oz MRWR#1 3 oz WR/R#6
Mixture #7 C1 20% F1 2 oz MRWR#3 3 oz WR/R#6
Mixture #8 C1 20% F2 2 oz MRWR#3 3 oz WR/R#6
Mixture #9 C1 20% F1 1 oz MRWR#4 2 oz WR/R#1
Mixture #10 C2 20% F1 1 oz MRWR#4 2 oz WR/R#1
Mixture #11 C1 20% F1 3 oz MRWR#1 2 oz WR/R#1
Mixture #12 C1 20% F2 3 oz MRWR#1 2 oz WR/R#1
Mixture #13 C2 20% F1 1 oz MRWR#4 6 oz WR/R#5
Mixture #14 C2 20% F2 1 oz MRWR#4 6 oz WR/R#5
Mixture #15 C3 20% F1 4 oz WR/R#2
Mixture #16 C3 20% F2 4 oz WR/R#2

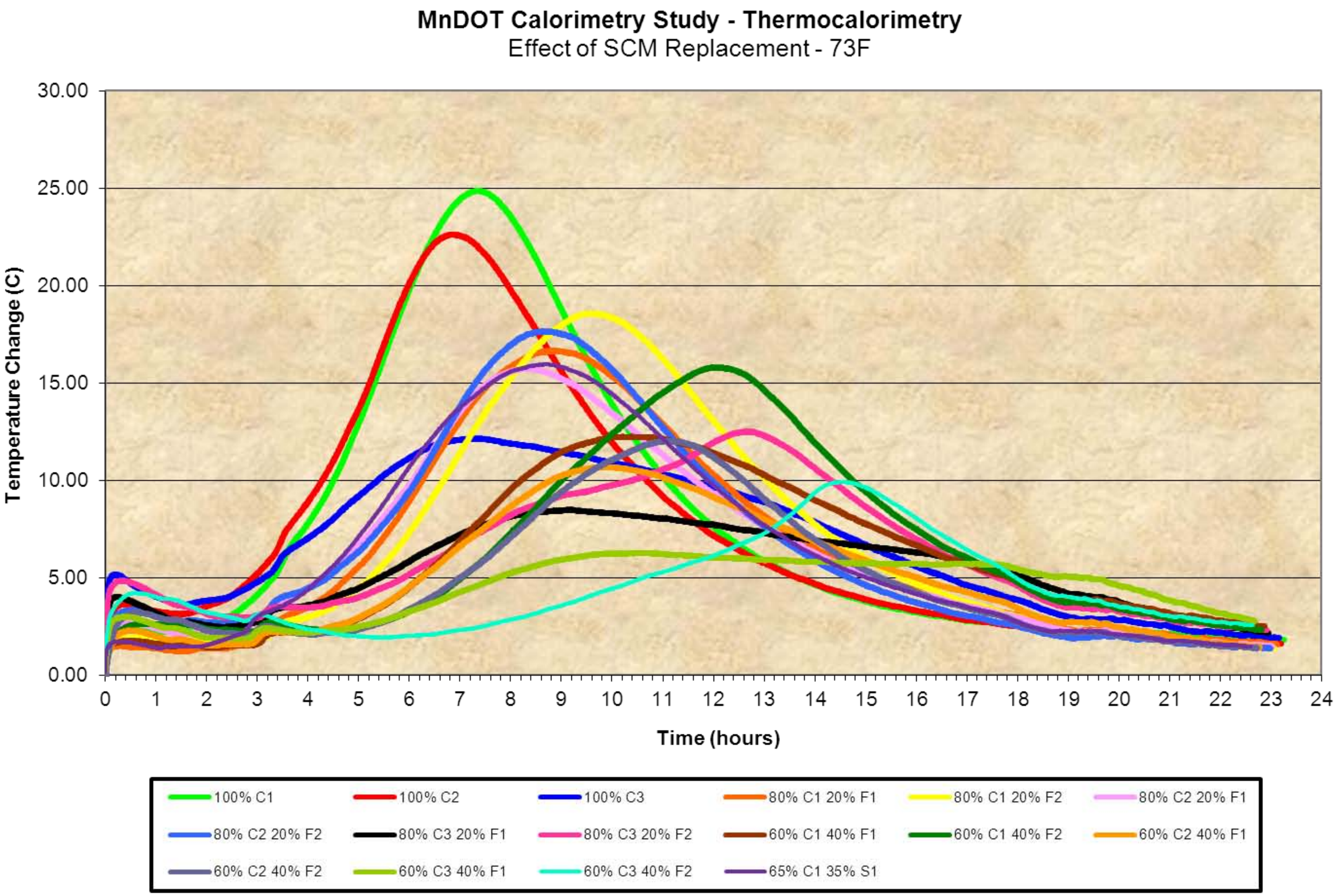

MnDOT Calorimetry Study - Thermocalorimetry - Cement #1
Effect of Admixtures - 73 F
Temperature Change (C)
30.00
25.00
20.00
15.00
10.00
5.00
0.00
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Time (hours)
100% C1
80% C1 20% F1
80% C1 20% F2
80% C1 20% F1 - 4 oz WR/R#2
80% C1 20% F2 - 4 oz WR/R#2
80% C1 20% F1 - 1 oz MRWR#4 6 oz WR/R#5
80% C1 20% F2 - 1 oz MRWR#4 6 oz WR/R#5
80%C1 20%F1 - 3 oz MRWR#1 2 oz WR/R#1
80%C1 20%F2 - 3 oz MRWR#1 2 oz WR/R#1
80%C1 20%F1 - 1 oz MRWR#4 2 oz WR/R#1
80%C1 20%F2 - 1 oz MRWR#4 2 oz WR/R#1
80% C1 20% F1 - 3 oz MRWR#1 3 oz WR/R#6
80% C1 20% F2 - 3 oz MRWR#1 3 oz WR/R#6
80% C1 20% F1 - 2 oz MRWR#3 3 oz WR/R#6
80% C1 20% F2 - 2 oz MRWR#3 3 oz WR/R#6



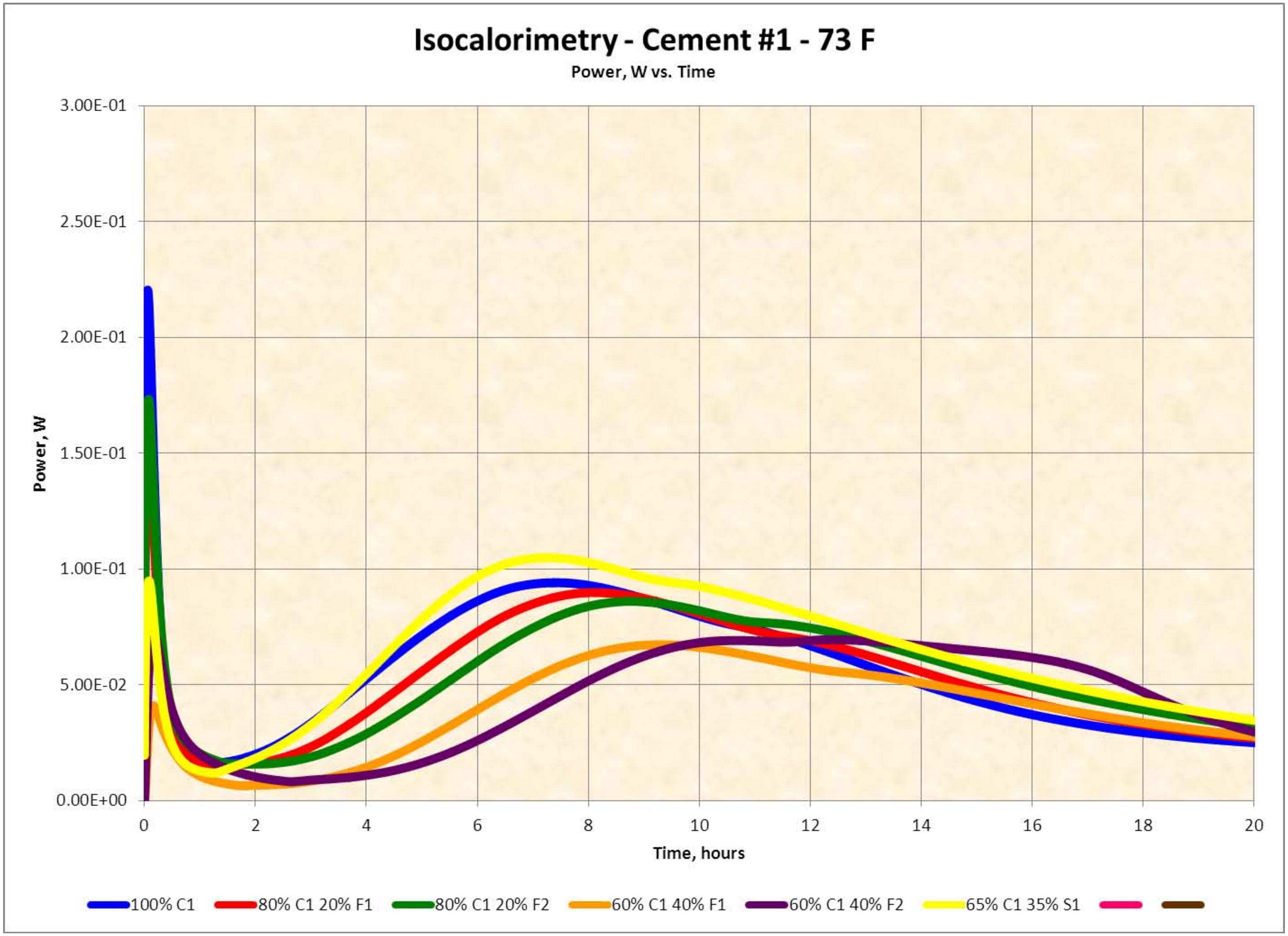
MnDOT Calorimetry Study - Thermocalorimetry - Cement #2
Effect of Admixtures - 73F
Temperature Change (C)
30.00
25.00
20.00
15.00
10.00
5.00
0.00
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Time (hours)
100% C2
80% C2 20% F1
80% C2 20% F2
80% C2 20% F1 - 4 oz WR/R#2
80% C2 20% F2 - 4 oz WR/R#2
80% C2 20% F1 - 1 oz MRWR#4 6 oz WR/R#5
80% C2 20% F2 - 1 oz MRWR#4 6 oz WR/R#5
80%C2 20%F1 - 3 oz MRWR#1 2 oz WR/R#1
80%C2 20%F2 - 3 oz MRWR#1 2 oz WR/R#1
80%C2 20%F1 - 1 oz MRWR#4 2 oz WR/R#1
80%C2 20%F2 - 1 oz MRWR#4 2 oz WR/R#1
80% C2 20% F1 - 3 oz MRWR#1 3 oz WR/R#6
80% C2 20% F2 - 3 oz MRWR#1 3 oz WR/R#6
80% C2 20% F1 - 2 oz MRWR#3 3 oz WR/R#6
80% C2 20% F2 - 2 oz MRWR#3 3 oz WR/R#6



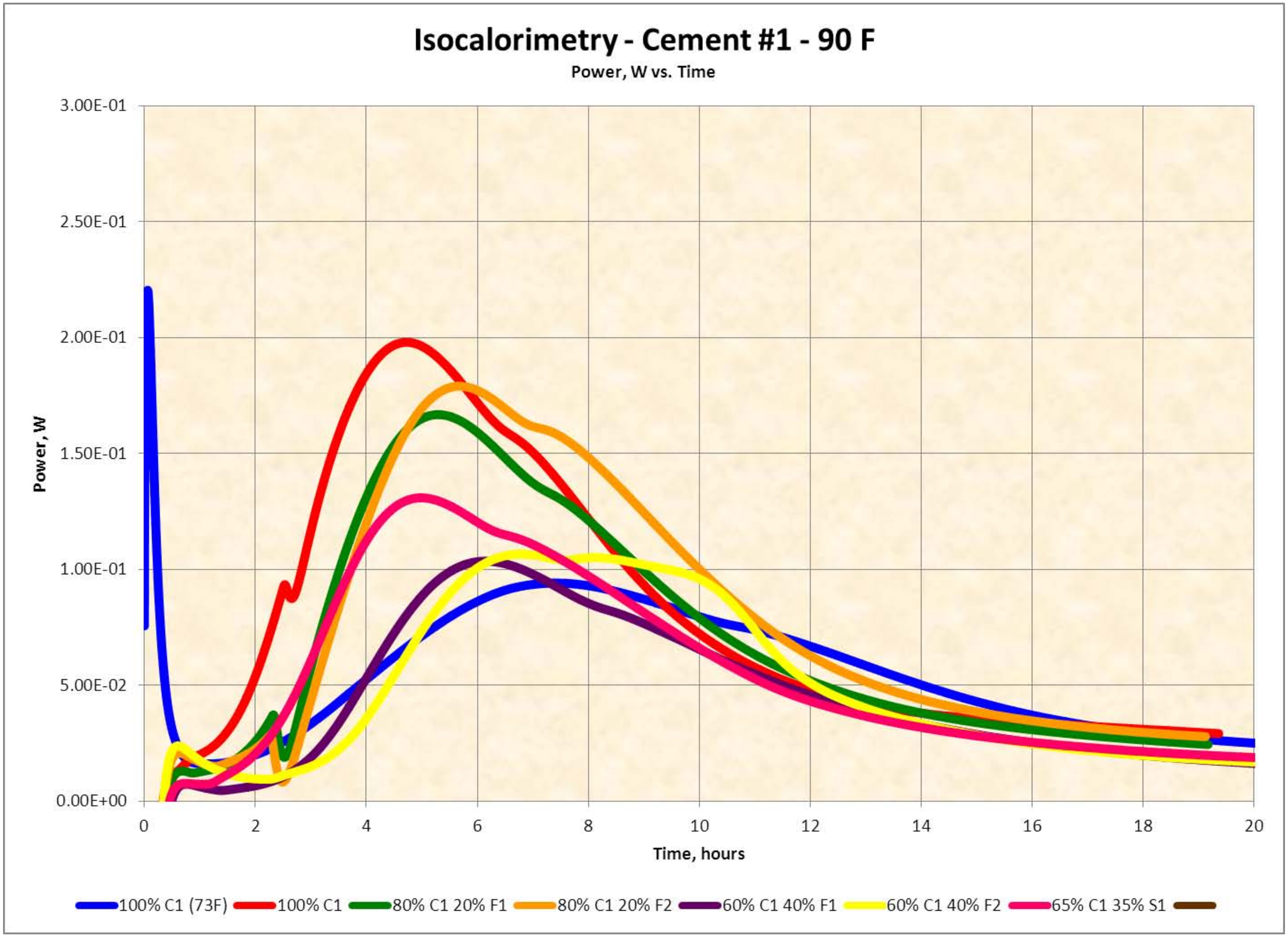
MnDOT Calorimetry Study - Thermocalorimetry - Cement #3
Effect of Admixtures - 73F
Temperature Change (C)
30.00
25.00
20.00
15.00
10.00
5.00
0.00
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Time (hours)
100% C3
80% C3 20% F1
80% C3 20% F2
80% C3 20% F1 - 4 oz WR/R#2
80% C3 20% F2 - 4 oz WR/R#2
80% C3 20% F1 - 1 oz MRWR#4 6 oz WR/R#5
80% C3 20% F2 - 1 oz MRWR#4 6 oz WR/R#5
80%C3 20%F1 - 3 oz MRWR#1 2 oz WR/R#1
80%C3 20%F2 - 3 oz MRWR#1 2 oz WR/R#1
80%C3 20%F1 - 1 oz MRWR#4 2 oz WR/R#1
80%C3 20%F2 - 1 oz MRWR#4 2 oz WR/R#1
80% C3 20% F1 - 3 oz MRWR#1 3 oz WR/R#6
80% C3 20% F2 - 3 oz MRWR#1 3 oz WR/R#6
80% C3 20% F1 - 2 oz MRWR#3 3 oz WR/R#6
80% C3 20% F2 - 2 oz MRWR#3 3 oz WR/R#6

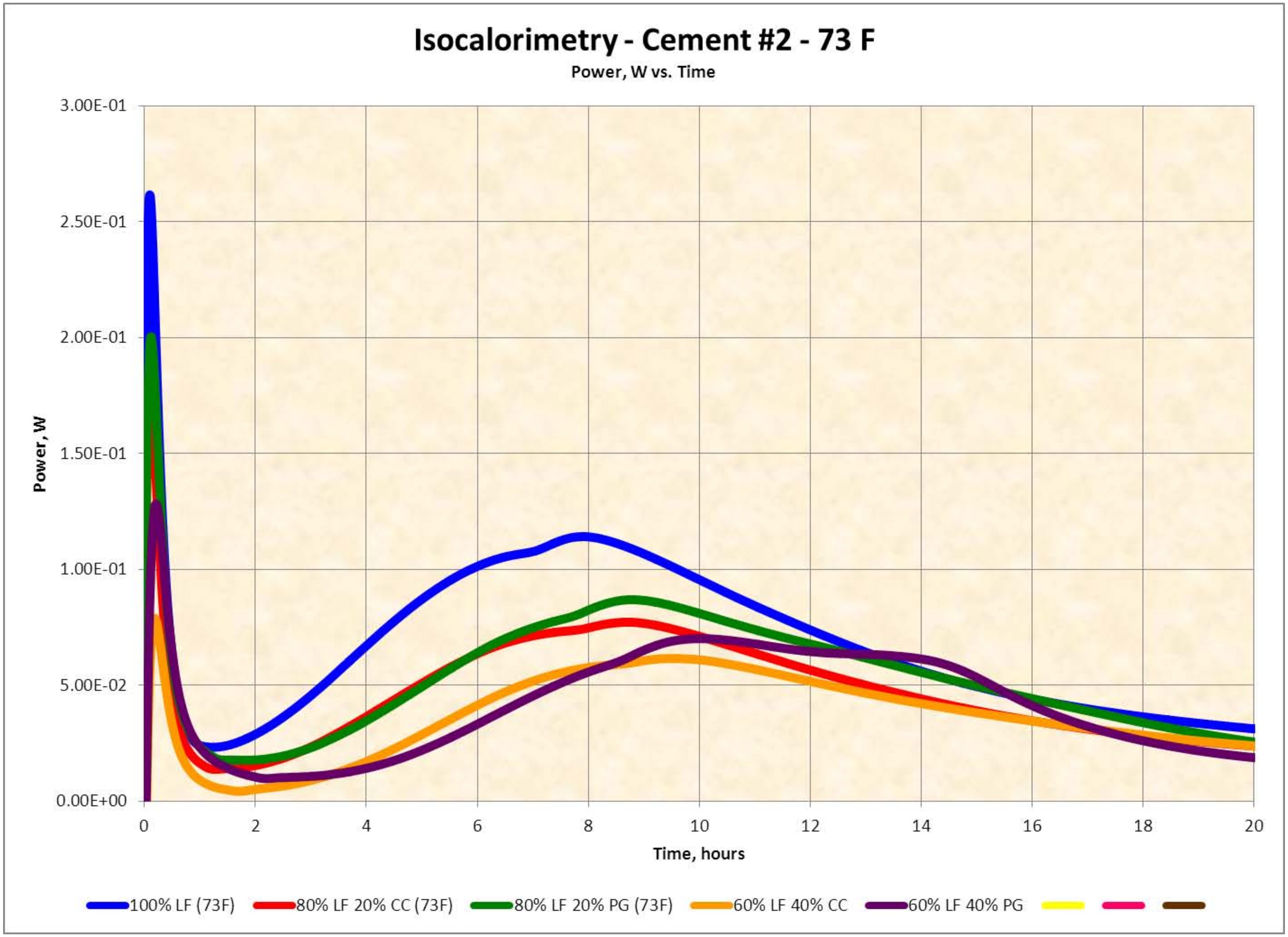

MnDOT Calorimetry Study - Thermocalorimetry
Effect of SCM Replacement - 73F
Temperature Change (C)
30.00
25.00
20.00
15.00
10.00
5.00
0.00
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Time (hours)
100% C1
100% C2
100% C3
80% C1 20% F1
80% C1 20% F2
80% C2 20% F1
80% C2 20% F2
80% C3 20% F1
80% C3 20% F2
60% C1 40% F1
60% C1 40% F2
60% C2 40% F1
60% C2 40% F2
60% C3 40% F1
60% C3 40% F2
65% C1 35% S1

APPENDIX G: ISOTHERMAL CALORIMETRY GRAPHS

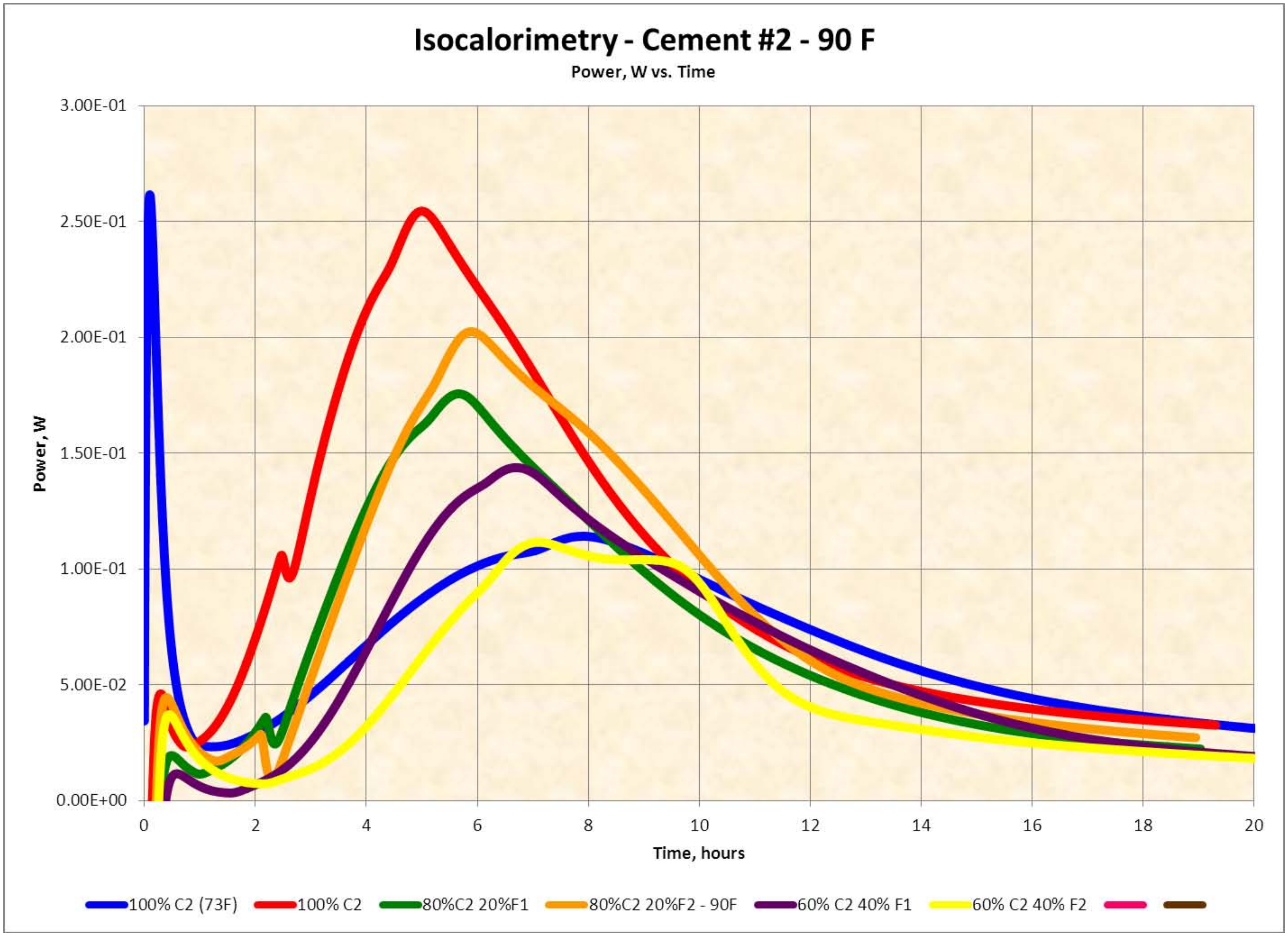


Isocalorimetry - Cement #1 - 73 F
Power, W vs. Time
3.00E-01
2.50E-01
2.00E-01
1.50E-01
1.00E-01
5.00E-02
0.00E+00
Power, W
0
2
4
6
8
10
12
14
16
18
20
Time, hours
100% C1
80% C1 20% F1
80% C1 20% F2
60% C1 40% F1
60% C1 40% F2
65% C1 35% S1

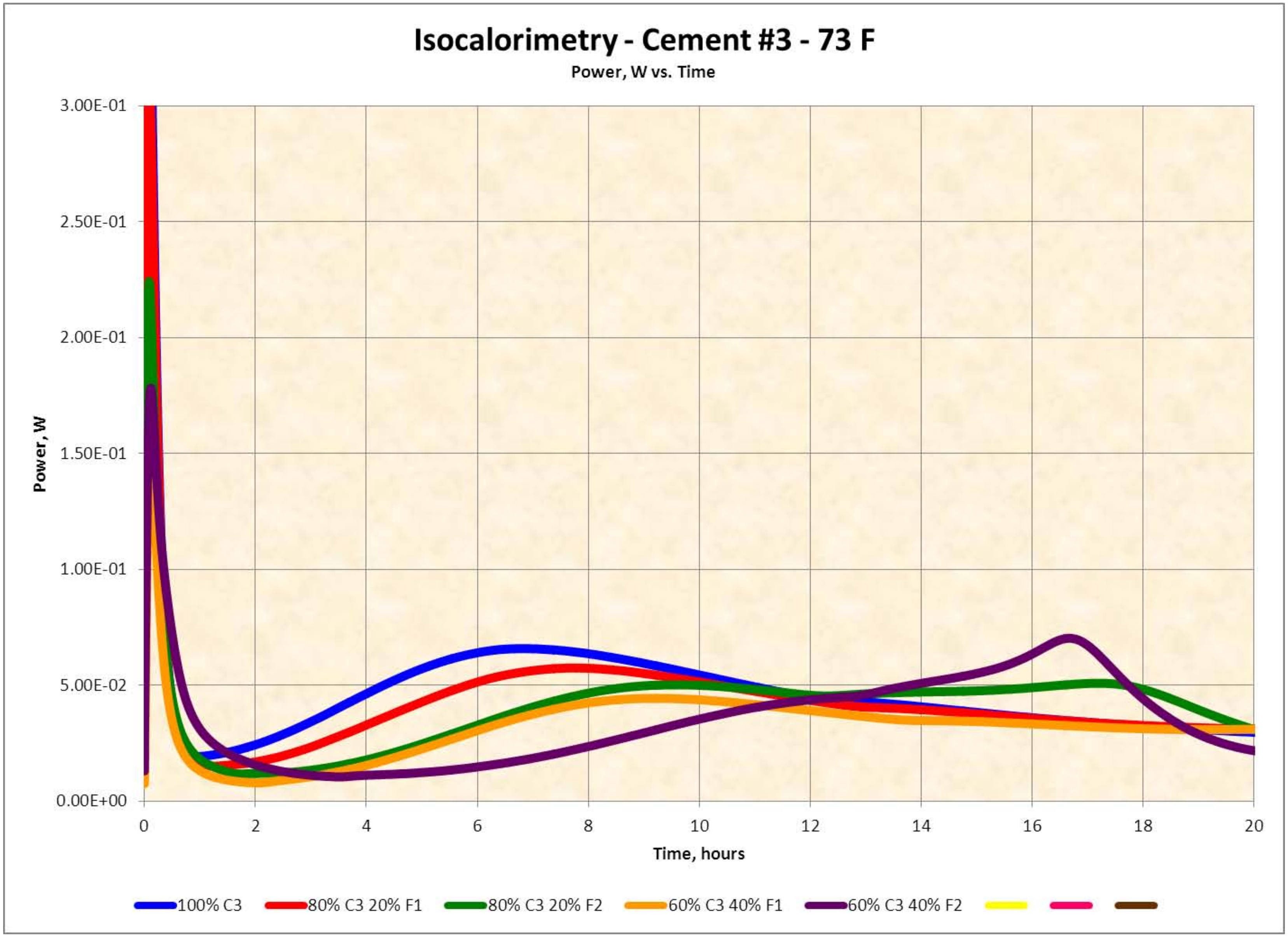

Isocalorimetry - Cement #1 - 90 F
Power, W vs. Time
Power, W
3.00E-01
2.50E-01
2.00E-01
1.50E-01
1.00E-01
5.00E-02
0.00E+00
0
2
4
6
8
10
12
14
16
18
20
Time, hours
100% C1 (73F)
100% C1
80% C1 20% F1
80% C1 20% F2
60% C1 40% F1
60% C1 40% F2
65% C1 35% S1



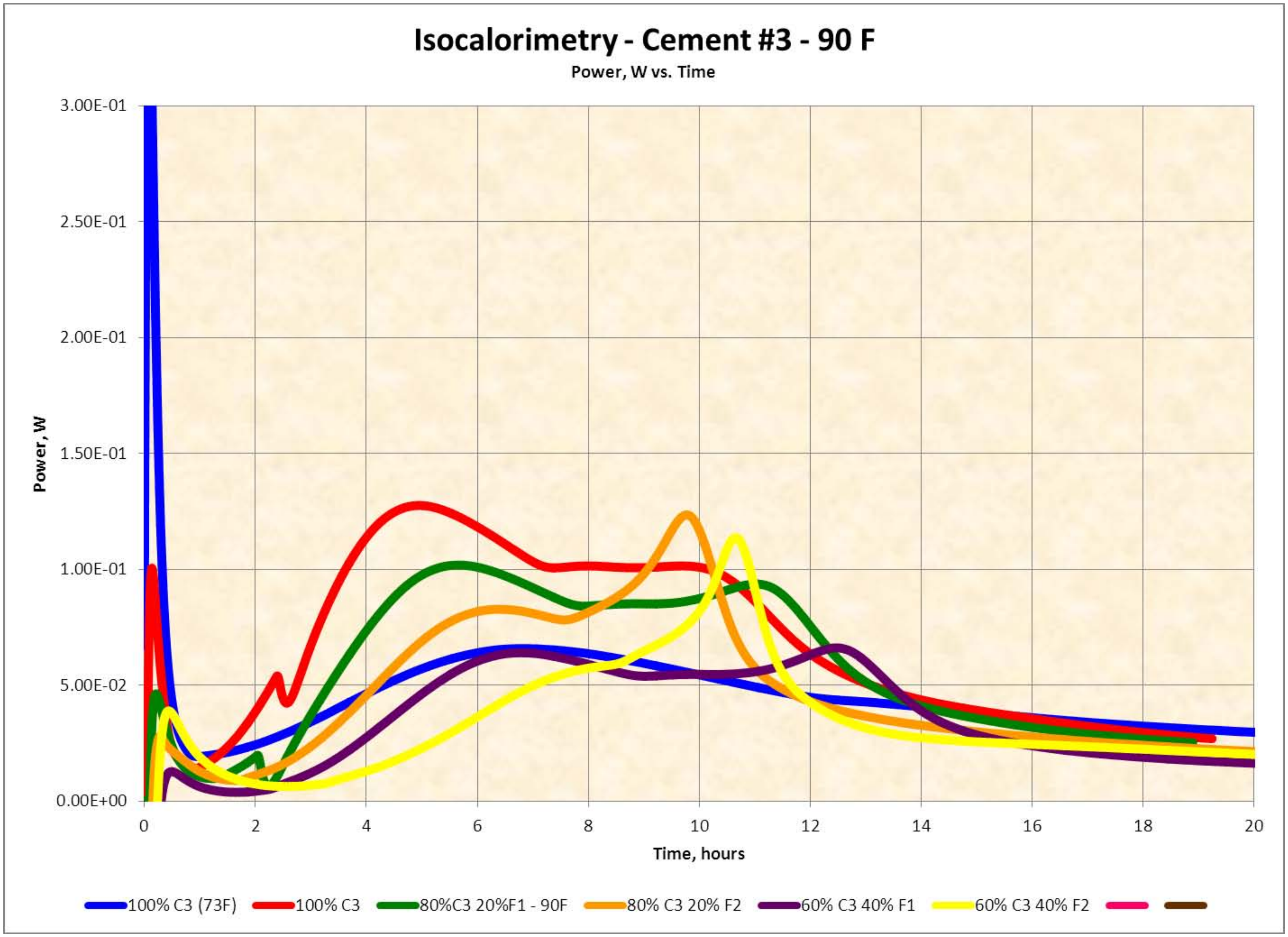
Isocalorimetry - Cement #2 - 73 F
Power, W vs. Time
Power, W
3.00E-01
2.50E-01
2.00E-01
1.50E-01
1.00E-01
5.00E-02
0.00E+00
0
2
4
6
8
10
12
14
16
18
20
Time, hours
100% LF (73F)
80% LF 20% CC (73F)
80% LF 20% PG (73F)
60% LF 40% CC
60% LF 40% PG



Isocalorimetry - Cement #2 - 90 F
Power, W vs. Time
3.00E-01
2.50E-01
2.00E-01
1.50E-01
1.00E-01
5.00E-02
0.00E+00
Power, W
0
2
4
6
8
10
12
14
16
18
20
Time, hours
100% C2 (73F)
100% C2
80%C2 20%F1
80%C2 20%F2 - 90F
60% C2 40% F1
60% C2 40% F2



Isocalorimetry - Cement #3 - 73 F
Power, W vs. Time
Power, W
3.00E-01
2.50E-01
2.00E-01
1.50E-01
1.00E-01
5.00E-02
0.00E+00
0
2
4
6
8
10
12
14
16
18
20
Time, hours
100% C3
80% C3 20% F1
80% C3 20% F2
60% C3 40% F1
60% C3 40% F2



Isocalorimetry - Cement #3 - 90 F
Power, W vs. Time
3.00E-01
2.50E-01
2.00E-01
1.50E-01
1.00E-01
5.00E-02
0.00E+00
Power, W
0
2
4
6
8
10
12
14
16
18
20
Time, hours
100% C3 (73F)
100% C3
80%C3 20%F1 - 90F
80% C3 20% F2
60% C3 40% F1
60% C3 40% F2