MCC Optimum Durability Study

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MCC's Cementitious Durability Study

DECEMBER, 2005 MINNESOTA CONCRETE COUNCIL

Optimum Mixes for Concrete Durability

The Minnesota Concrete Council is conducting its most comprehensive and exciting study to establish optimum mixes for concrete durability. The study is being led by a cooperative task force consisting of Alf Gardner (Holcim, Inc), Jamison Langdon (Braun Intertec), Kevin MacDonald (Cemstone Concrete Products), David Morlock (Lafarge North America), Michael Ramerth (Meyer, Borgman, & Johnson), Mike Thomes (Xcel Energy) and Dan Vruno (American Engineering Testing, Inc.). The task force has been successful in enlisting the help of three independent testing laboratories (American Engineering Testing, Inc., Braun Intertec Corporation and Stork/Twin City Testing, Corporation) to do the batching, testing, and reporting of the various mixes within the study design. MCC members have contributed the aggregates, mineral admixtures, liquid admixtures, and cement to complete the study.

MCC is a nonprofit organization dedicated to the education and leading edge technology with respect to cast-in-place concrete. The durability study is a perfect fit with our mandate and should benefit our members and the industry in general. Prior to the study design, the MCC task force researched some 39 other studies which explored the durability issue. However, with today's pressure to reduce the waste stream and to think "green" with respect to the components comprising the various mixes, the task force incorporated micro silica, fly ash, and slag as mineral admixtures to the cementitious content.

What is concrete durability?

Durable hydraulic-cement concrete has the ability to resist weathering action, chemical attack, abrasion, or any other process of deterioration. Durable concrete will retain its original form and quality, regardless of service environment. Research has indicated that concrete durability is largely dependent on the permeability of the concrete in terms of reducing the potential for either liquids or gases to enter and pass through the concrete.

Parameters Impacting Concrete Durability

Experience has shown that the major causes for concrete deterioration are exposure to cycles of freezing and thawing, alkali silica reactivity, sulfate attack, and corrosion of reinforcing steel. Water plays an important role in all four of these parameters through the mechanism of expansion and associated cracking.

A simplistic approach would consider increasing the proportion of cement to improve water tightness of the concrete. However, research has shown that increasing the cement content increases the potential for both drying and thermal shrinkage of concrete, leaving the concrete susceptible to equal or greater water ingress. Thus, cement content of a mix does not control its durability. Rather, durability depends largely on the properties of the hydrated cement paste and therefore, the cement content of the paste itself is relevant. Keeping the water to cementitious content as low as possible and the aggregate content as high as possible is an excellent strategy to reduce both the drying and thermal shrinkage as well as related cracking. The MCC study will take advantage of this strategy. Previous studies on mineral admixtures have indicated that blast furnace slag and micro silica both offer resistance to chloride-ion by reducing the permeability of the cement paste. By its very nature, micro silica reduces concrete permeability during the early stages of concrete curing whereas fly ash and slag are more effective at a somewhat latter age.

Study Design

The MCC study will consist of 19 mixes based on consistent water to cementitious ratio and consistent workability.

What will vary will be the proportions of the mineral admixtures (micro silica, slag, and fly ash) to judge their influence in optimizing the durability of the various mixes. The latter stages of the program include flexibility of adjustments to the batching proportions, which may be indicative after review of the Phase 1 and Phase 2 preliminary data.

Phase I

Mix Performance Parameters

Researchers understand that changing a quality or component of a complex system is likely to affect another quality of the system. To evaluate the performance of the various mixes and potential impact on the properties of the concrete, the following series of tests will be conducted*:*

1. Plastic Properties Testing
   - Unit Weight
   - Slump
   - Air Content
2. Initial Time of Set (ASTM:C403)
3. Compressive Strength Testing (ASTM:C39)
4. Rapid Chloride Permeability Testing (ASTM:C1202)
5. Scaling Resistance (ASTM:C672)
6. Shrinkage Testing (ASTM: C157)

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Phase I Results

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Performance Specification

A Guide for the MCC Research Program on Optimum Durability

- Compressive Strength Req. f 'c=3,000 psi/30 hours
  f 'c=6,000 psi/28 days
- Except for the "control mixes", all test mixes should include a minimum of 30% (total) recycled pozzolans as a Portland cement replacement. The maximum replacement of recycled pozzolans should be limited as follows:
  - Fly Ash 35%
  - Slag 35%
  - Micro Silica 4%
- The total pozzolan content shall be limited to 658# (7 bag mix)
- The maximum water cement ratio shall be .42
- The aggregate shall be well graded with a maximum size of 1 1/2". The aggregate gradation must be consistent throughout all batching. All large aggregate shall be limestone. (No less than 55% of the aggregate (by weight) shall be retained on the #4 sieve.)
- All test mixes shall be air entrained to 6%± 1 %. The selected AEA shall be consistent throughout all batching.
- Corrosion inhibitors shall <u>not</u> be added to any of the test mixes
- All WRA's shall be a polycaboxilate and shall be a consistent brand throughout all batching.
- The performance criteria for permeability shall be as follows:
  - 6 months ≤ 1000 coulombs
  - 12 months ≤ 500 coulombs
- The performance criteria for drying shrinkage shall limit the average length change in 6 months to -0.050%.
- The performance criteria for deicing scaling is that the blended pozzolan test mixes shall perform as well or better than the control mixes which contain only the Portland cement.
- There shall be no autogenous shrinkage cracking.
- There shall be no plastic shrinkage cracking.

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What is Concrete Durability?

- Durability of concrete is defined as its ability to resist weathering action, chemical attack, abrasion, or any other process of deterioration.
- Durable concrete will retain its original form, quality, and serviceability, when exposed to its service environment.
- Concrete durability is largely dependent on the ease with which liquids and/or gasses enter into and move through the concrete. This is commonly referred to as the permeability of concrete.

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MCC Durable Cementitious Study

Batch No.		% Cement	% Micro Silica	% Slag	% Fly Ash
1.	PC	100	0	0	0
2.	30S	70	0	30	0
3.	30FA	70	0	0	30 (F)
4.	30S, 1MS	69	1	30	0
5.	30FA, 1MS	69	1	0	30 (F)
6.	30S, 3MS	67	3	30	0
7.	30FA, 3MS	67	3	0	30 (F)
8.	PC	100	0	0	0
9.	30CA	70	0	0	30 (C)
10.	30CA, 1MS	69	1	0	30 (C)
11.	30CA, 3MS	67	3	0	30 (C)
12.	20S, 20FA	60	0	20	20 (F)
13.	20S, 20CA	60	0	20	20 (C)
14.	1MS, 20S, 20FA	59	1	20	20 (F)
15.	1MS, 20S, 20CA	59	1	20	20 (C)
16.	3MS, 20S, 20FA	57	3	20	20 (F)
17.	3MS, 20S, 20CA	57	3	20	20 (C)
18.	*1MS, 30CA	69	1	0	30 (C)
19.	**30CA	70	0	0	30 (C)

*Batch 18 is the same as Batch 10, except no DCI

** Batch 19 is the same a Batch 9, except the water cementitious ratio is 0.50

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Identification Scheme

20% Slag

3MS, 20S, 20FA

3% Micro Silica

20% Type F Fly Ash

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Batching Data

	Batch No.							
	1 PC	**2 30S**	**3 30FA**	**4 30S, 1MS**	**5 30FA, 1MS**	**6 30S, 3MS**	**7 30FA, 3MS**	**8 PC**
% Micro Silica	0	0	0	1	1	3	3	0
% Slag	0	30	0	30	0	30	0	0
% Fly Ash	0	0	30	0	30	0	30	0
Portland I/II (lbs)	658	461	461	454	454	441	441	611
Micro Silica (lbs)	0	0	0	6.6	6.6	19.7	19.7	0
Slag (lbs)	0	197.4	0	197.4	0	197.4	0	0
Fly Ash (lbs)	0	0	197.4	0	197.4	0	197.4	0
Total Cementitious (lbs)	658	658	658	658	658	658	658	611
Well Graded Aggregates (lbs)	3111	3111	3111	3111	3111	3111	3111	3177
WRA (High Range) (cwt)	5.3	5.0	4.8	5.1	5.0	4.7	4.5	5.3
Corrosion Inhibitor (gallons)	3	3	3	3	3	3	3	3
Total Water	263	263	263	263	263	263	263	244
W/C	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Air Entraining (cwt)	.9	1.2	1.1	1.2	1.0	1.0	1.1	.90
Test Results								
Slump (in)	5	6 ½	7 ½	7	7	5	6	7
Air Content (%)	6.2	5.0	6.1	6.0	7.2	5.4	7.2	6.4
Unit Weight (lb/ft^3)	146.8	147.2	146.8	146.1	145.9	147.0	146.4	146.0
Initial Set (hr:min)	3:33	4:30	4:45	4:50	4:47	4:50	5:15	4:00

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Batching Data

	9 30CA	10 30CA, 1MS	11 30CA, 3MS	12 20S, 20FA	13 20S, 20CA	14 1MS, 20S, 20FA	15 1MS, 20S, 20CA	16 3MS, 20S, 20FA	17 3MS, 20S, 20CA	18 1MS, 30CA	19 30CA
% Micro Silica	0	1	3	0	0	1	1	3	3	1	0
% Slag	0	0	0	20	20	20	20	20	20	0	0
% Fly Ash	30	30	30	20	20	20	20	20	20	30	30
Portland I/II (lbs)	461	454	441	395	395	388	388	375	375	454	461
Micro Silica (lbs)	0	6.6	19.7	0	0	6.6	6.6	19.7	19.7	6.6	0
Slag (lbs)	0	0	0	131.6	131.6	131.6	131.6	131.6	131.6	0	0
Fly Ash (lbs)	197.4	197.4	197.4	131.6	131.6	131.6	131.6	131.6	131.6	197.4	197.4
Total Cementitious (lbs)	658	658	658	658	658	658	658	658	658	658	658
Well Graded Aggregates (lbs)	3111	3111	3111	3111	3111	3111	3111	3111	3111	3111	3111
WRA (High Range) (cwt)	4.8	5.0	5.0	4.6	4.6	4.7	4.7	5.0	5.0	5.1	2.0
Corrosion Inhibitor (gal)	3	3	3	3	3	3	3	3	3	0	3
Total Water	263	263	263	263	263	263	263	263	263	263	328
W/C	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5
Air Entraining (cwt)	1.1	1.2	1.2	1.0	1.0	1.1	1.1	1.2	1.2	1.2	.9
Test Results											
Slump (in)	6 ½	6 ½	5	7 ½	7	7	5	7	5	4 ½	8
Air Content (%)	5.0	6.2	5.0	6.5	5.1	5.4	6.0	6.2	7.1	5.0	5.5
Unit Weight (lb/ft^3)	147.3	146.8	147.5	146.0	147.0	147.2	146.4	146.8	146.1	147.3	146.8
Initial Set (hr:min)	4:20	4:30	4:40	4:37	4:05	4:41	4:10	4:45	4:14	5:01	4:49

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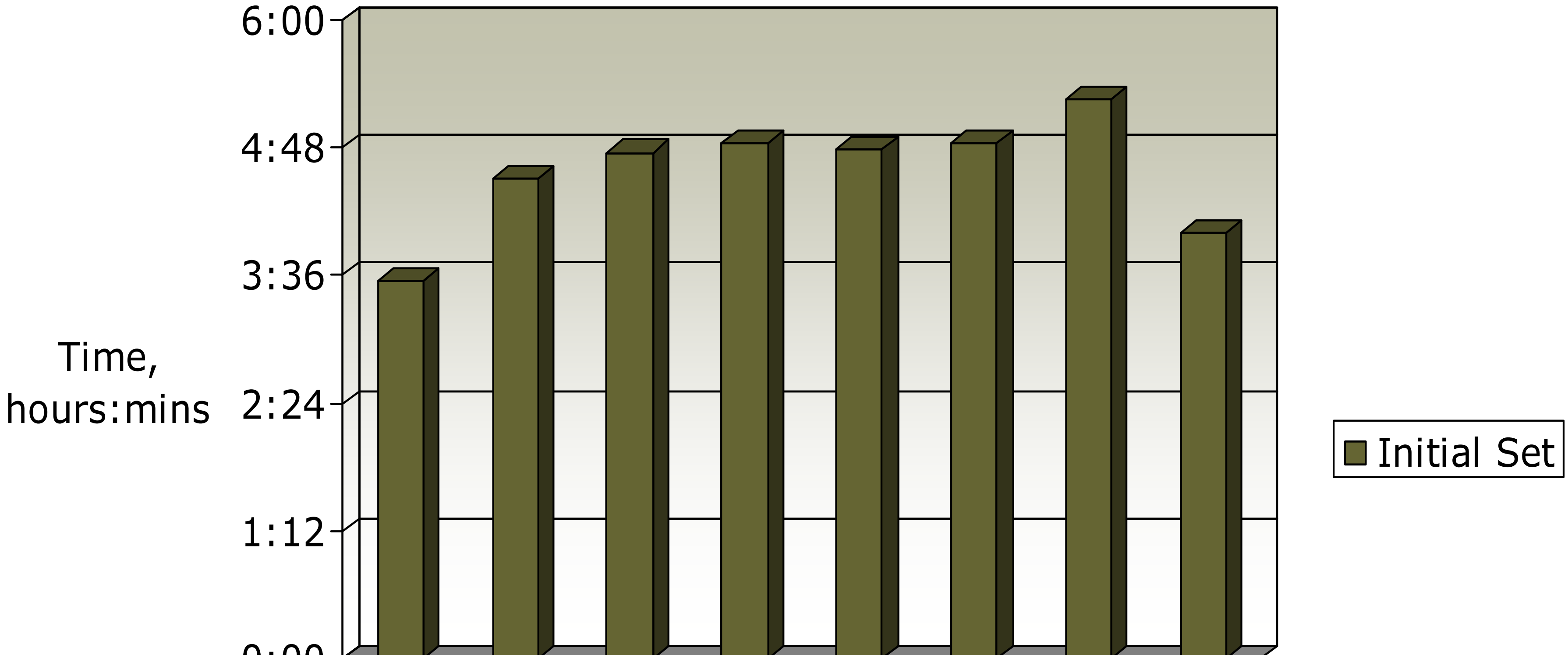
Time of Set



	(#1) PC	(#2) 30S	(#3) 30FA	(#4) 30S, 1MS	(#5) 30FA, 1MS	(#6) 30S, 3MS	(#7) 30FA, 3MS	(#8) PC
Initial Set	3:33	4:30	4:45	4:50	4:47	4:50	5:15	4:00

Mix Design

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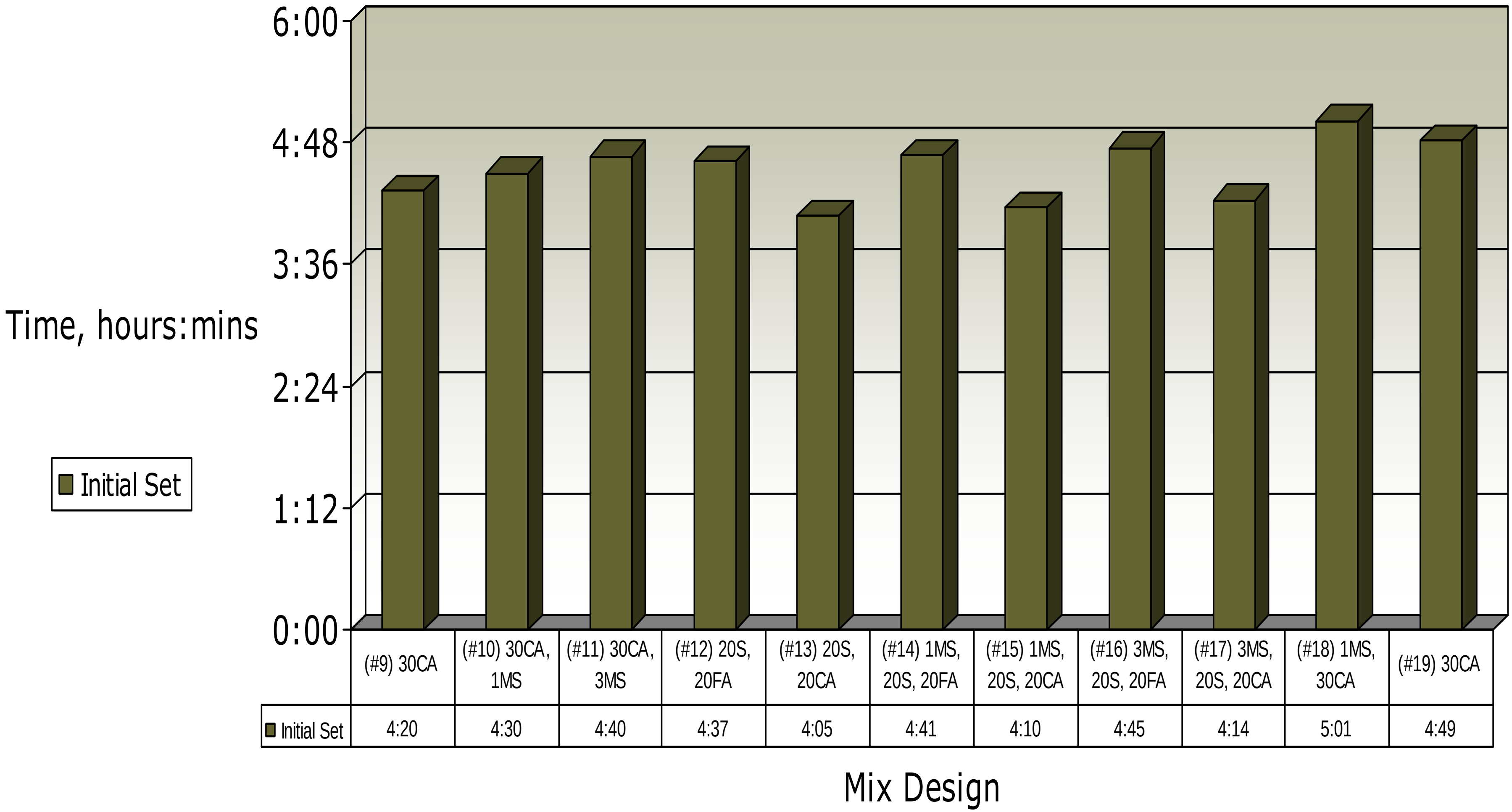
Time of Set



	(#9) 30CA	(#10) 30CA, 1MS	(#11) 30CA, 3MS	(#12) 20S, 20FA	(#13) 20S, 20CA	(#14) 1MS, 20S, 20FA	(#15) 1MS, 20S, 20CA	(#16) 3MS, 20S, 20FA	(#17) 3MS, 20S, 20CA	(#18) 1MS, 30CA	(#19) 30CA
Initial Set	4:20	4:30	4:40	4:37	4:05	4:41	4:10	4:45	4:14	5:01	4:49

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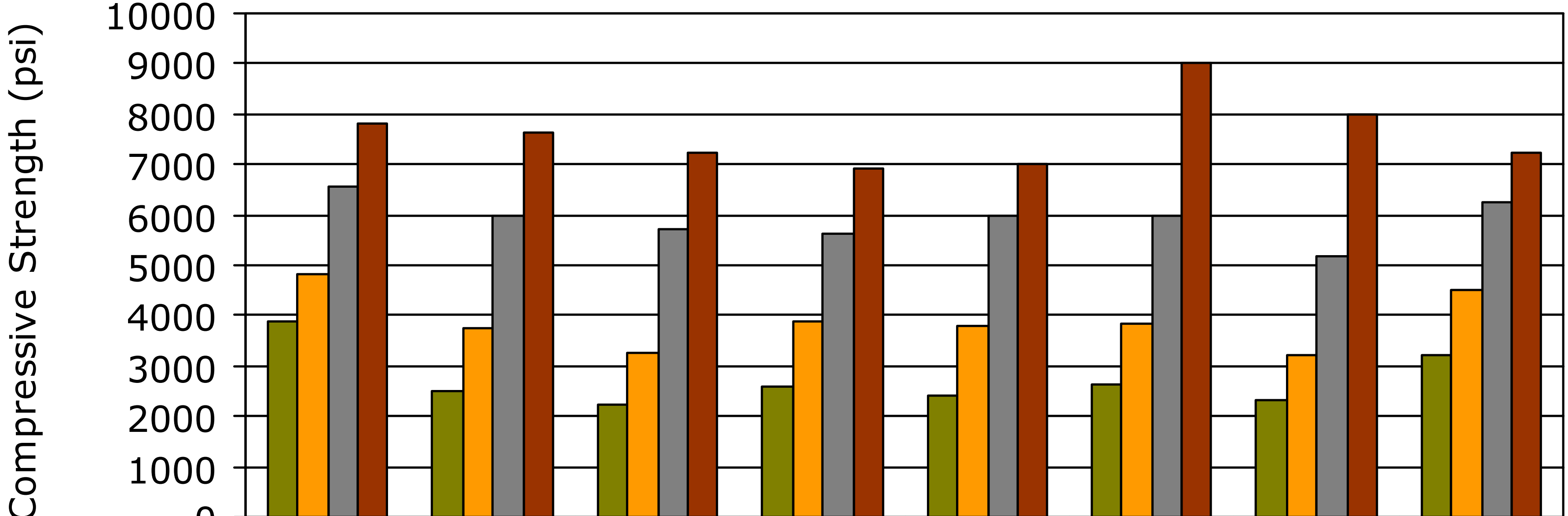
Average Compressive Strength (psi)



	(#1) PC	(#2) 30S	(#3) 30FA	(#4) 30S, 1MS	(#5) 30FA, 1MS	(#6) 30S, 3MS	(#7) 30FA, 3MS	(#8) PC
1 Day	3870	2495	2240	2580	2400	2635	2300	3200
2 Days	4810	3740	3250	3900	3780	3845	3210	4510
7 Days	6580	5970	5710	5645	5960	6000	5200	6230
28 Days	7820	7650	7230	6910	7010	9040	7980	7220

Mix Design

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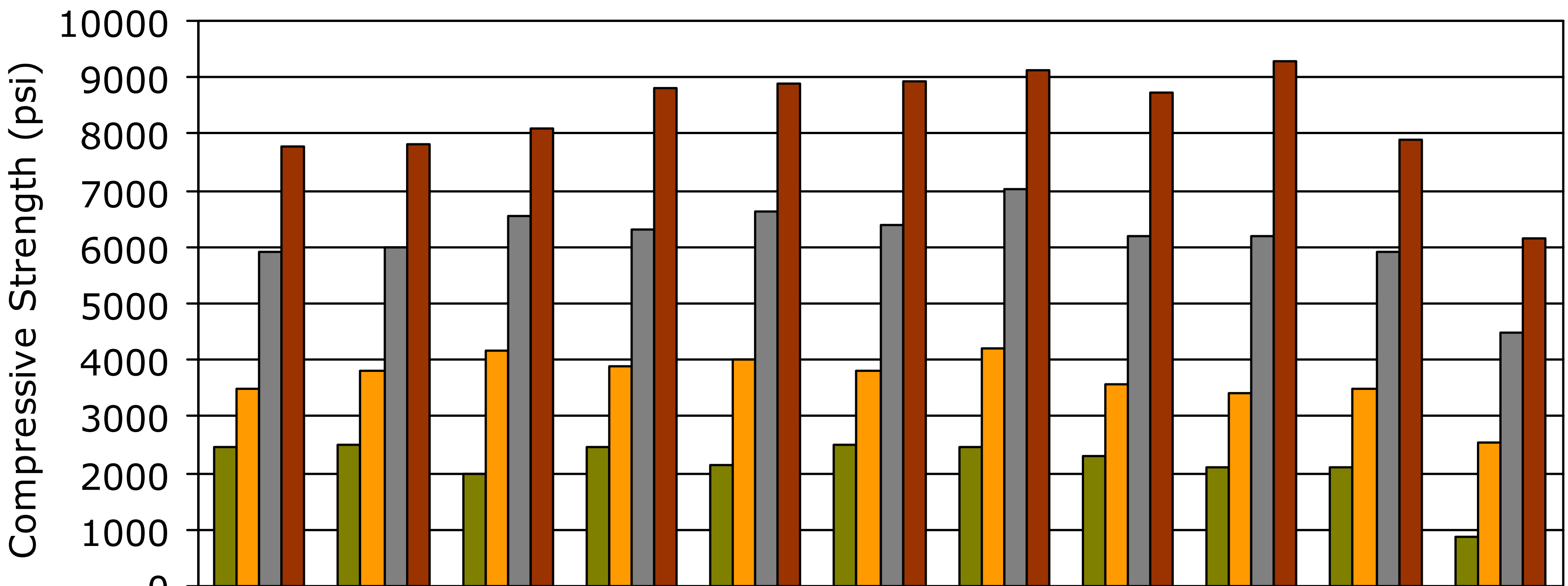
Average Compressive Strength (psi)



	(#9) CA	(#10) 30CA, 1MS	(#11) 30CA, 3MS	(#12) 20S, 20FA	(#13) 20S, 20CA	(#14) 1MS, 20S, 20FA	(#15) 1MS, 20S, 20CA	(#16) 3MS, 20S, 20FA	(#17) 3MS, 20S, 20CA	(#18) 1MS, 30CA	(#19) 30CA
1 Day	2470	2490	1995	2470	2150	2490	2460	2290	2095	2100	885
2 Days	3480	3800	4165	3885	3992	3805	4200	3565	3395	3495	2535
7 Days	5920	6000	6530	6325	6630	6385	7030	6195	6200	5905	4480
28 Days	7770	7800	8093	8825	8900	8915	9145	8735	9275	7890	6150

Mix Design

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Rapid Chloride Permeability Test

•History of Rapid Chloride Permeability Test:

The rapid chloride permeability test (RCP) was created in the early 1980s and was adopted by both AASHTO T 277 and ASTM:C1202.

•RCP Test:

In the RCP test, saturated 2" thick by 4" diameter concrete discs are prepared and subjected for 6 hours to direct electric current having a potential difference of 60 volts.

•Charge Passage vs. Permeability:

Based on experimental evidence, a low passage of charge in this test, on the whole, indicates low chloride permeability, and a high charge passage indicates high chloride permeability.

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Chloride Permeability Based On Charge Passed

Charge Passed, Coulombs	Chloride Permeability
>4000	High
2000 – 4000	Moderate
1000 – 2000	Low
100 – 1000	Very Low
<100	Negligible

Source: AASHTO T227 or ASTM:C1202

RCP Testing

					RCP Results Coulombs	
Batch No.	% Cement	% Micro Silica	% Slag	% Fly Ash	56 Days	6 Months
1. PC	100	0	0	0		1281
2. 30S	70	0	30	0		1066
3. 30FA	70	0	0	30 (F)		366
4. 30S, 1MS	69	1	30	0		606
5. 30FA, 1MS	69	1	0	30 (F)		269
6. 30S, 3MS	67	3	30	0		620
7. 30FA, 3MS	67	3	0	30 (F)		305
8. PC	100	0	0	0		1427
9. 30CA	70	0	0	30 (C)	1869	590
10. 30CA, 1MS	69	1	0	30 (C)	2519	955
11. 30CA, 3MS	67	3	0	30 (C)	1952	876
12. 20S, 20FA	60	0	20	20 (F)	1034	386
13. 20S, 20CA	60	0	20	20 (C)	986	347
14. 1MS, 20S, 20FA	59	1	20	20 (F)	707	292
15. 1MS, 20S, 20CA	59	1	20	20 (C)	1046	445
16. 3MS, 20S, 20FA	57	3	20	20 (F)	717	263
17. 3MS, 20S, 20CA	57	3	20	20 (C)	732	313
18. *1MS, 30CA	69	1	0	30 (C)	1433	538
19. **30CA	70	0	0	30 (C)	2624	893

*Batch 18 is the same as Batch 10, except no DCI
**Batch 19 is the same as Batch 8, except the water cementitious ratio is 0.50.

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Altered Electrical Properties Effect on RCP Test Results

Some concretes can have altered electrical properties and can give false readings. When we compare Batch 18 to Batch 10 in our study, Batch 10 passed twice the charge as Batch 18. The tests suggests the difference in the RCP test values result from the inclusion of a Corrosion Inhibitor in Batch 18. The additional ions contributed by the inhibitor increases the passage of electrical charges during the test.

Another example of altered electrical properties which can give false reading is the use of pozzolans that tie up normally free ions within the concrete pours. The reduced ion concentration results in less charge being passed.

This is not to say that concrete with pozzolans have lower chloride permeability, but may not be as low as the rapid test indicates.

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RCP Testing

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Drying Shrinkage Data

CONCRETE SHRINKAGE DATA, ASTM:C157, MODIFIED CURING AIR DRYING										
Batch No.	7-Day Lime Water	4-Day	7-Day	14-Day	21-Day	28-Day	2-Month	4- Month	6-Month	9-Month
1. PC	0.001	-0.010	-0.015	-0.022	-0.026	-0.029	-0.040	-0.049	-0.050	-0.060
2. 30S	0.009	-0.015	-0.026	-0.035	-0.039	-0.041	-0.048	-0.052	-0.053	-0.057
3. 30FA	0.008	-0.014	-0.025	-0.036	-0.040	-0.043	-0.053	-0.059	-0.068	-0.064
4. 30S, 1MS	0.007	-0.015	-0.024	-0.034	-0.039	-0.042	-0.050	-0.056	-0.057	-0.063
5. 30FA, 1MS	0.008	-0.010	-0.018	-0.025	-0.033	-0.037	-0.045	-0.048	-0.048	-0.053
6. 30S, 3MS	0.007	-0.005	-0.008	-0.016	-0.024	-0.026	-0.033	-0.039	-0.040	-0.045
7. 30FA, 3MS	0.010	-0.009	-0.015	-0.028	-0.038	-0.039	-0.047	-0.050	-0.050	-0.055
8. PC	0.014	-0.002	-0.006	-0.019	-0.028	-0.030	-0.041	-0.051	-0.053	-0.066
9. 30CA	0.007	-0.023	-0.028	-0.035	-0.041	-0.045	-0.050	-0.061	-0.061	-0.065
10. 30CA, 1MS	0.012	-0.019	-0.031	-0.038	-0.045	-0.047	-0.052	-0.062	-0.062	-0.065
11. 30CA, 3MS	-0.006	-0.028	-0.035	-0.039	-0.044	-0.046	-0.050	-0.060	-0.061	-0.066
12. 20S, 20FA	0.001	-0.018	-0.028	-0.034	-0.042	-0.048	-0.052	-0.059	-0.061	-0.065
13. 20S, 20CA	-0.008	-0.026	-0.037	-0.040	-0.044	-0.047	-0.051	-0.061	-0.062	-0.050
14. 1MS, 20S, 20FA	0.005	-0.023	-0.034	-0.039	-0.041	-0.045	-0.049	-0.060	-0.061	-0.056
15. 1MS, 20S, 20CA	0.015	-0.020	-0.023	-0.028	-0.034	-0.035	-0.043	-0.047	-0.047	-0.050
16. 3MS, 20S, 20FA	0.010	-0.016	-0.025	-0.033	-0.038	-0.040	-0.047	-0.051	-0.052	-0.056
17. 3MS, 20S, 20CA	0.010	-0.022	-0.034	-0.040	-0.044	-0.048	-0.051	-0.060	-0.062	-0.064
18. *1MS, 30CA	-0.003	-0.023	-0.033	-0.038	-0.043	-0.046	-0.049	-0.057	-0.059	-0.063
19. **30CA	0.002	-0.025	-0.037	-0.044	-0.052	-0.057	-0.067	-0.075	-0.077	-0.089

*Batch 18 is the same as Batch 10, except no DCI **Batch 19 is the same as Batch 8, except the water cementitious ratio is 0.50.

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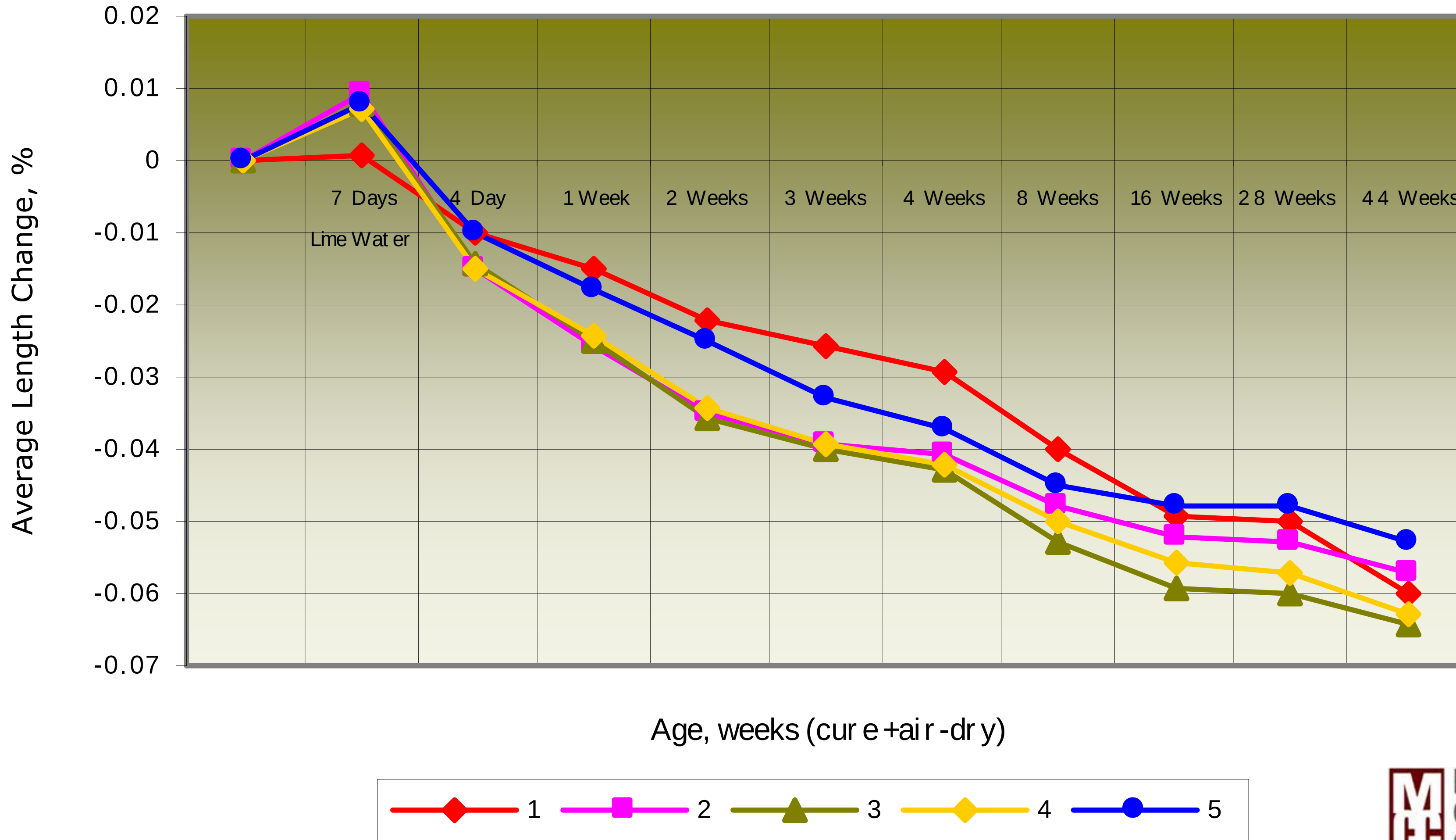
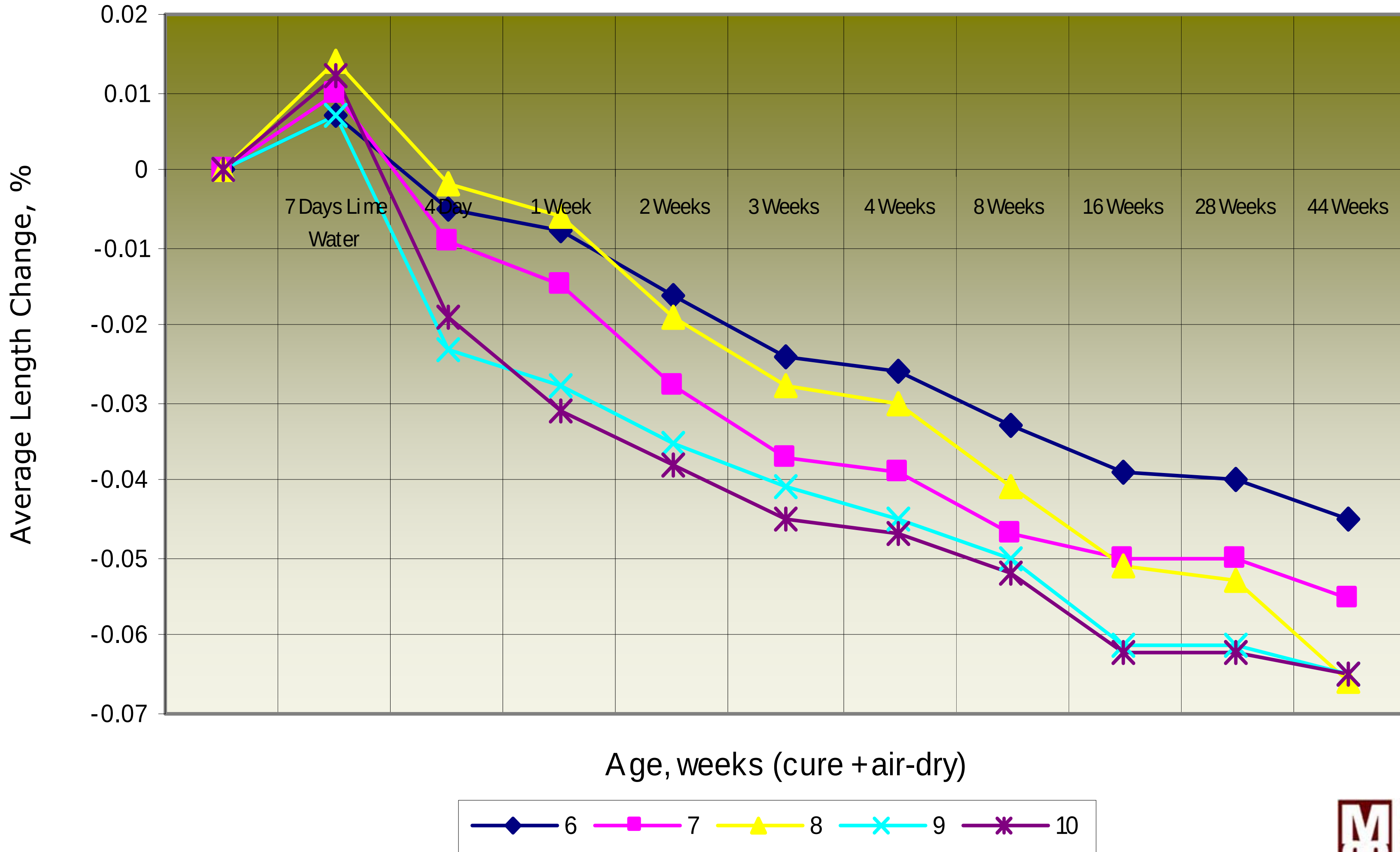
ASTM: C157 Drying Shrinkage

Sets 1, 2, 3, 4 and 5



ASTM: C157 Drying Shrinkage

Sets 6, 7, 8, 9 and 10



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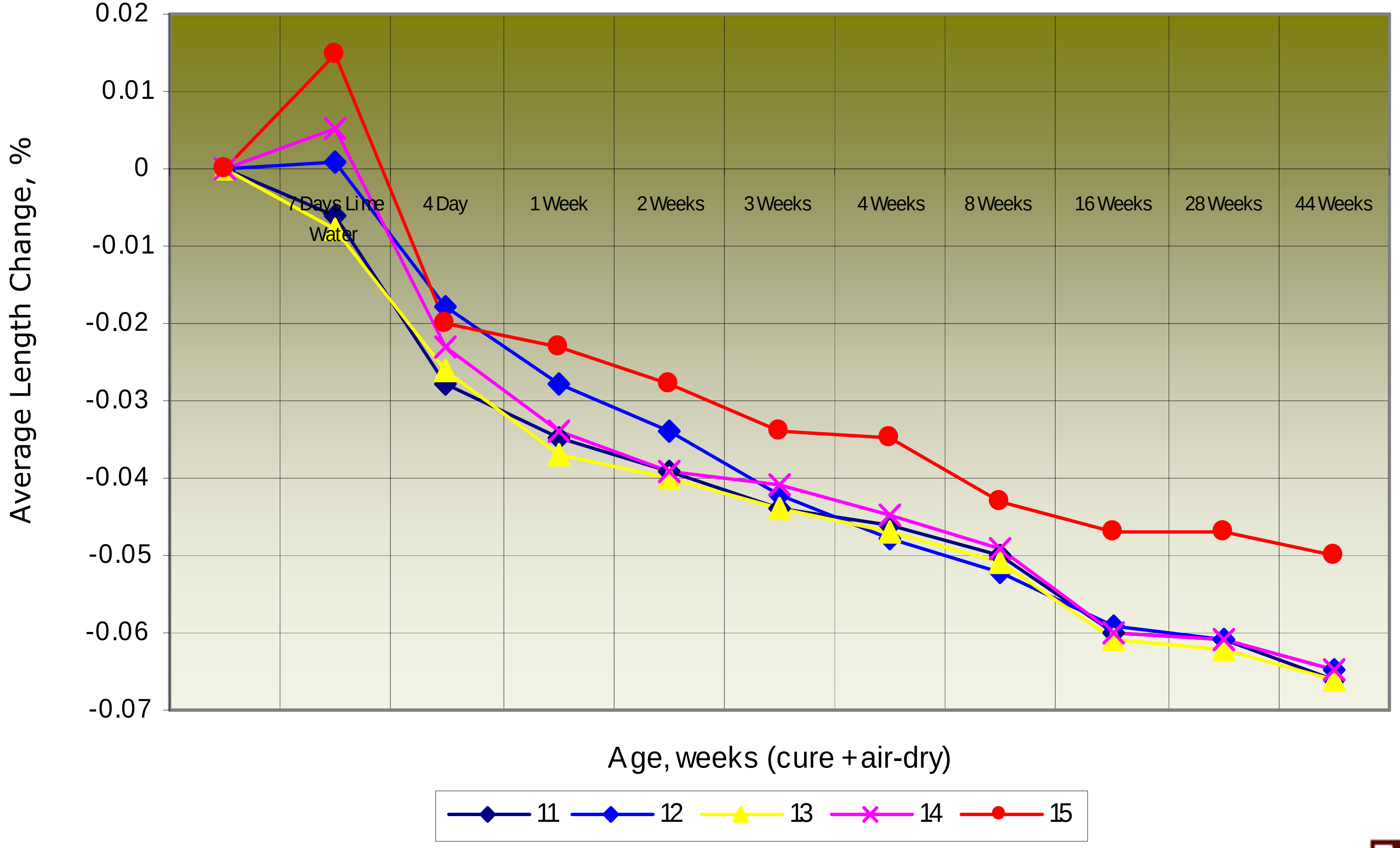
ASTM: C157 Drying Shrinkage

Sets 11, 12, 13, 14 and 15



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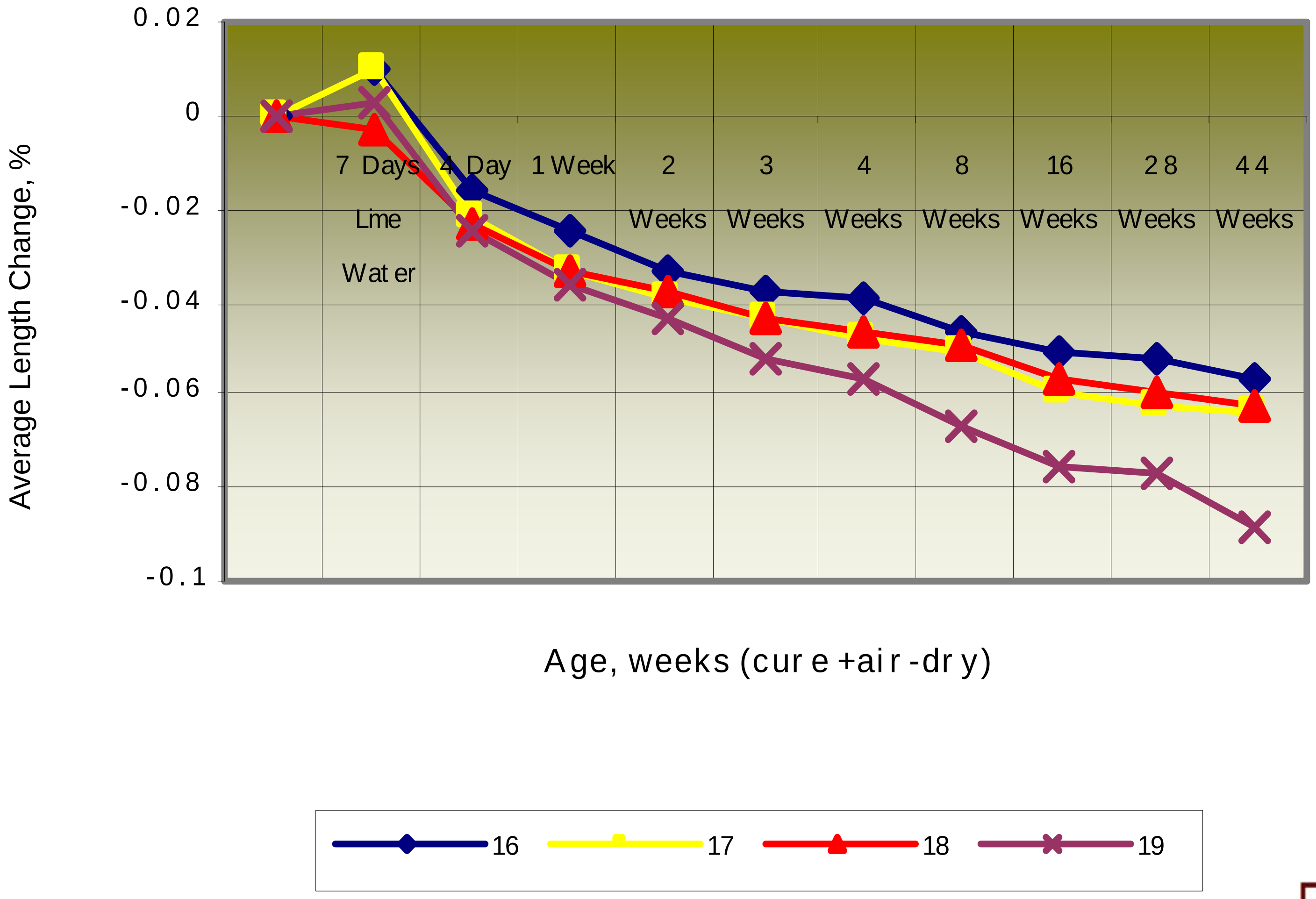
ASTM: C157 Drying Shrinkage

Sets 16, 17, 18 and 19



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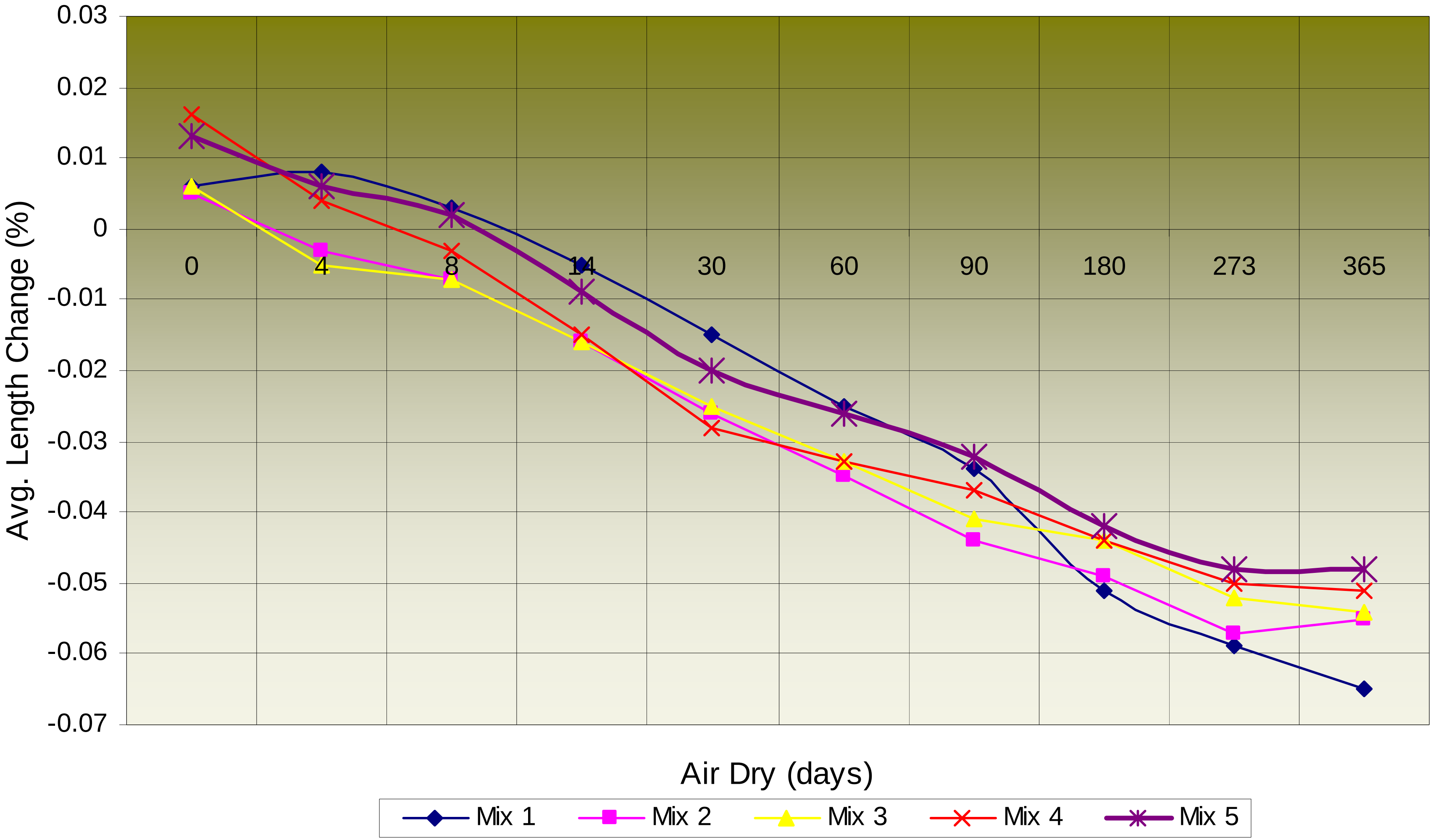
MCC SHRINKAGE STUDY FROM 1999



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MCC Shrinkage Study

Mix No.	Composition
1	6 sacks cement, 3/4" gravel
2	6 sacks cement, 12" optimized gradation
3	6 sacks cement, 12" optimized gradation, high range water reducer
4	6 sacks cement/15% fly ash, 12" optimized gradation
5	6 sacks cement/15% fly ash, 12" optimized gradation, high-range water reducer

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Scaling Resistance Test

- **Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals**

  This test method covers the determination of the resistance to scaling of a horizontal concrete surface exposed to freezing-and-thawing cycles in the presence of deicing chemicals (ASTM C672/672M-98).

- **Basic Test Procedure**

  Create test specimens as prescribed, then place a 1” high dike around the perimeter of the specimen in order to pond a ¼” deep solution of calcium chloride and water. Then subject the specimen to repeated freezing-and-thawing cycles.

- **Rating System**

  0 No Scaling
  1 Very light scaling (1/8” depth max., no coarse aggregate visible)
  2 Slight to moderate scaling
  3 Moderate scaling (some coarse aggregate visible
  4 Moderate to severe scaling
  5 Severe scaling (coarse aggregate visible over entire surface)

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Scaling After 50 Cycles – Panels #1-2

Batch No. #1
Rating: 2

Batch No. #2
Rating: 2

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Scaling After 50 Cycles – Panels #3-4

Batch No. #3
Rating: 3

Batch No. #4
Rating: 2

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Scaling After 50 Cycles – Panels #5-6

Batch No. #5
Rating: 3

Batch No. #6
Rating: 1

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Scaling After 50 Cycles – Panels #7-8

Batch No. #7
Rating: 2

Batch No. #8
Rating: 3

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Scaling After 50 Cycles – Panels #9 & 11

Batch No. #9
Rating: 2

Batch No. #11
Rating: 2

Scaling After 50 Cycles – Panels #12-13

Batch No. #12
Rating: 2

Batch No. #13
Rating 3

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Scaling After 50 Cycles – Panels #14-15

Batch No. #14
Rating: 0

Batch No. #15
Rating: 0

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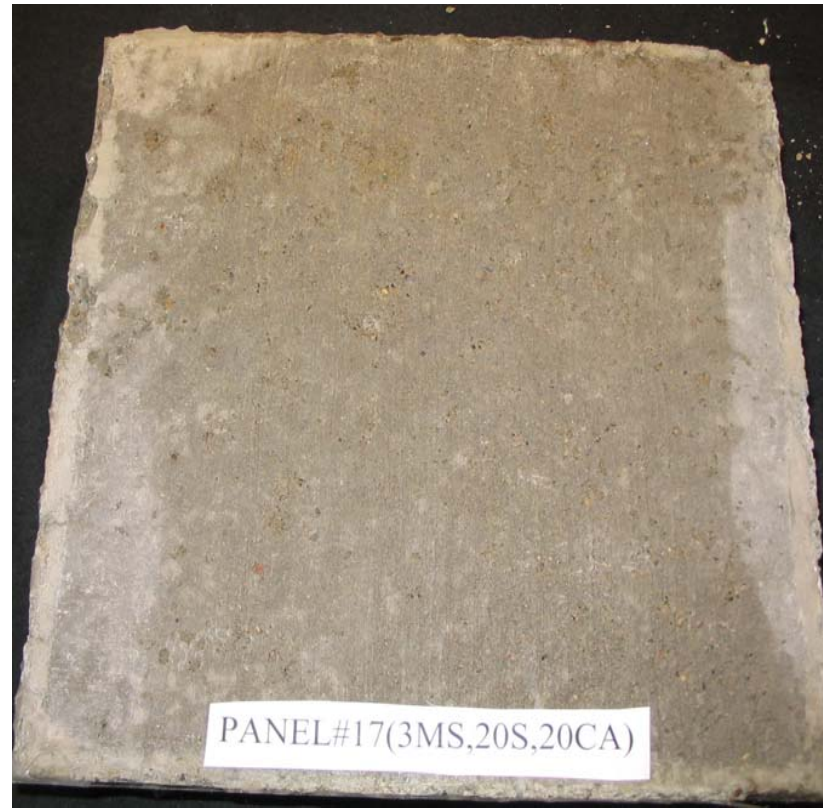
Scaling After 50 Cycles- Panels #16-17

Batch No. #16
Rating: 2



Batch No. #17
Rating: 2

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Scaling After 50 Cycles – Panels #18-19

Batch No. #18
Rating: 3

Batch No. #19
Rating: 3

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Scaling Results

Batch No.	Identification	Rating after 50 Cycles
1	PC	2
2	30S	2
3	30FA	3
4	30S, 1MS	2
5	30FA, 1MS	3
6	30S, 3MS	1
7	30FA, 3MS	2
8	PC	3
9	30CA	2
11	30CA, 3MS	2
12	20S, 20FA	2
13	20S, 20CA	3
14	1MS, 20S, 20FA	0
15	1MS, 20S, 20CA	0
16	3MS, 20S, 20FA	2
17	3MS, 20S, 20CA	2
*18	1MS, 30CA	3
**19	30CA	3

*Batch 18 is the same as Batch 10, except no DCI
**Batch 19 is the same as Batch 8, except the water cementitious ratio is 0.50.

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