Establishing Optimum Mixture Proportions for Concrete Durability Using Supplementary Cementitious Material

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1 INTRODUCTION

The Minnesota Concrete Council (MCC) Charter states, "Our purpose is to be on the leading edge in cast-in-place concrete technology and to educate our members as well as the general public." Through a cooperative effort of its members, both the specifiers and the end-users were educated in the use of supplementary cementitious material (SCM).

There exists an inherent separation between what can be demonstrated in the laboratory and what can constructed in the field. This separation between theory and practice in concrete can be traced back to the time of Vitruvius, over 2,000 years ago. In the laboratory we can limit the independent variables and levels to perform a factorial, statistically based research study. In the field the variability of temperature, mixing, transport, placement, finishing, curing, and environmental exposure greatly increases the independent variables which complicates the statistic. It took a cooperative effort of both specifiers and end-users to perform this research on the use of SCM's.

2 USE OF SCM's

SCM products have been used for the past four decades in our area. Originally, the use of lignite fly ash as a partial replacement for Portland cement was the end result of another study to find a use for a waste product. The turn of the century coincided with the emergence of a new philosophy with regard to the use of alternate cementitious materials. This philosophy, based on the purposeful reuse of waste stream materials, embraces incorporating various combinations of cement, granulated slag, fly ash, and micro silica in the production of concrete. In light of environmental controls on the production of cement, shortages of suitable source materials and an ever-growing worldwide demand for concrete. MCC believed this new approach was here to stay. What was exciting was the fact that these alternate materials used individually or in concert, improved compressive strength, water tightness, shrinkage control, workability and thermal characteristics. SCM's can boost the durability of a mixture and reduce the associated generation of CO_2.

Increasing the resistance of concrete to penetration of chloride-ion is the "first line of defense" in increasing the service life of concrete structures. The use of fly ash through its combination with calcium, potassium and sodium hydroxides to produce calcium silicate hydrates increases the resistance of concrete to penetration of chloride-ions. Fly ash reduces permeability, thereby reducing access by aggressive chemicals, oxygen, and moisture [Kreck 1997].

When both fly ash and silica fume are used as SCM's, the silica fume decreases the chloride-ion penetrability at an early age and the fly ash decreases it at later age, resulting in a concrete with very low chloride-ion penetrability at both 28 and 120 days.

Concrete containing both ground granulated blast furnace slag and silica fume offer particularly good resistance to chloride-ions. Silica fume reduces the permeability of the transition zone around the aggregate particles, as well as the permeability of the bulk cement paste [Neville 1997].

Incorporating slag, fly ash, and silica fumes as SCM's in concrete, restructures size and spacing of the pores which helps resist chloride-ion penetration. The most promising aspect of utilizing SCM's is that not only will we be responsible stewards of this planet, we will also be producing a more durable concrete.

3 STUDY STRATEGY

Research has shown that increasing the cement content of a mix increases the potential for both drying and thermal shrinkage of hardened concrete, leaving the concrete susceptible to equal or greater water ingress. Contrary to conventional thinking, cement content of a mix does not control its durability. Durability depends largely on the properties of the hydrated cement paste and therefore, the cement content of the paste itself is relevant. Keeping the paste content as low as possible and the aggregate content as high as possible was the strategy chosen to reduce both the drying and thermal shrinkage as well as related cracking, while optimizing durability.

Given the above considerations, the establishment of the various mixes included in the study, supplying of materials and the batching and testing has required a cooperative effort of our members as well as financial and technical assistance from ARM (Aggregate Ready Mix of Minnesota).

The performance of the mixes chosen to be evaluated is based on testing the following properties:

- Initial Time of Set and Drying Shrinkage (ASTM:C403)
- Compressive Strength (ASTM:C39)
- Shrinkage Testing (ASTM:C157)
- Scaling Resistance (ASTM:C672)
- Rapid Chloride Permeability Testing (ASTM:C1202)
- Finishability Rating

Considering the number of mix variations the study was complex. However, to keep the scope of the program as controlled as possible, specific parameters were essentially fixed to best illustrate past performance, with variations in cementitious constituents. For example, the following controls were incorporated into the program:

- All mixes were designed to achieve compressive strength of 3000 psi in 30 hours and 6000 psi in 28 days.
- Recyclable by-product replacement would not exceed 35% fly ash, 35% slag, and 4% silica fume.
- Total cementitious contents would not exceed 658 lbs (7 bag mix).
- Maximum W/cm of 0.42
- Aggregate gradations, types, and proportions were the same for all mixes.
- Entrained air content to be within a range of 6% +/- 1%.
- Water reducing admixtures restricted to polycarboxilates.
- Average drying shrinkage in 6 months should be less than 0.05%.
- Rapid chloride permeability to be less or equal to 1000 coulombs in 6 months.
- Scaling of blended mixes shall perform as well or better than control mixes of Portland cement.

4 LABORATORY STUDY (PHASE I)

The first step of the original study included a literature search for available published data on optimized mixes using "waste stream" Pozzolan. The literature search indicated that new environmental controls on the production of cement would drive the industry to using greater percentages of recycled Pozzolan. The study committee felt there were multiple reasons for using these secondary materials. These alternative materials used separately, or in concert with others, greatly improve strength, water tightness, shrinkage control, workability, thermal characteristics and durability. Of equal importance to the study, was for the mixes to have similar placement and curing properties as conventional concrete for the craftspeople doing the installation and finishing work.

The laboratory work (Phase I) was designed to explore the durability of nineteen concrete mixes. All concrete mixes were produced at a 0.40 water/cementitious ratio with a 5.0 to 7.0% air content. The total cementitious content was 658 pounds per yard. Various combinations of micro silica, slag, and fly ash were utilized in the creation of the nineteen test mixes.

Part of the test program was documenting the typical plastic concrete properties. Concrete set times were measured and compressive strengths were determined at 1, 7, and 28 days. The durability testing consisted of rapid chloride permeability tests (ASTM: C1202), drying shrinkage (ASTM: C157), and scaling resistance (ASTM: C67).

A key was assigned to the mix identification to portray the type and percentages of cementitious constituents. For example, Mix 17 was designated as 17-3MS, 20S, 20CA, which indicates the mix contains 3% silica fume, 20% slag, and 20% Type C fly ash. Mixes 1-PC and 8-PC are both for control (at two different cementitious contents) and contain only Portland cement as the cementitious material. The symbol FA indicates Type F fly ash as a cementitious replacement (see Table 1 for a total list of proportions).

Table 1. Mix Variations and Proportions

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 corrosion inhibitor
**Batch 19 is the same as Batch 9, except the water cementitious ratio is 0.50.

The laboratory results were presented by Michael Ramerth at the University of Minnesota 57th Annual Concrete Conference and by Daniel Vruno at the International Sustainable Concrete Materials and Technologies Conference held in England in 2007. An electronic version of this published paper is available on the MCC website. A review of the laboratory study resulted in MCC narrowing our focus to nine mixes.

5 JATC LOCAL 633 (PHASE II)

Tom Reger, Apprentice Coordinator, Cement Masons, Plasterers, and Shophands; Dan Vruno, Member of the MCC Laboratory Design Team

Based on the results from the laboratory study, the following nine mixes (Table 1) were chosen for the field study:

Mix No. 1	PC
Mix No. 2	30S
Mix No. 3	30FA
Mix No. 4	30S, 1MS
Mix No. 6	30S, 3MS
Mix No. 11	30CA, 3MS
Mix No. 14	1MS, 20S, 20FA
Mix No. 15	1MS, 20S, 20CA
Mix No. 17	3MS, 20S, 20CA

In May and September of 2006, local ready mix producers delivered concrete to JATC Local 633 facility in New Brighton, Minnesota. The success of this Phase II study was mixed. Our plastic test results and durability testing were not sufficiently consistent with the laboratory results to consider publishing the results. Rather, efforts were directed at determining what factors influenced the inconsistencies of the Phase II results. Subsequent petrographic work revealed that the percentages of recyclable material varied from the design, thus affecting the test results.

It was important to the research team to determine what went wrong and to learn from it. The team decided that more control was needed of the material quantities and the batching sequence, also the load sizes were increased to 9 cubic yards. The team determined that one ready mix plant should be utilized for batching the mixes (two were used in the Phase II studies). A "practice" run was performed the day before the placement date.

6 BATCH PLANT PLACEMENT (PHASE III)

Phase III placement at AVR

Phase III placement at AVR

The ready mix supplier (AVR) did an excellent job of dialing in the mixes the day before the Phase III placement.

On May 28, 2009, volunteer members of MCC were successful in producing, placing, finishing, and testing the nine chosen mixes below. The table also indicates the plastic properties of the various mixes documented during the placement.

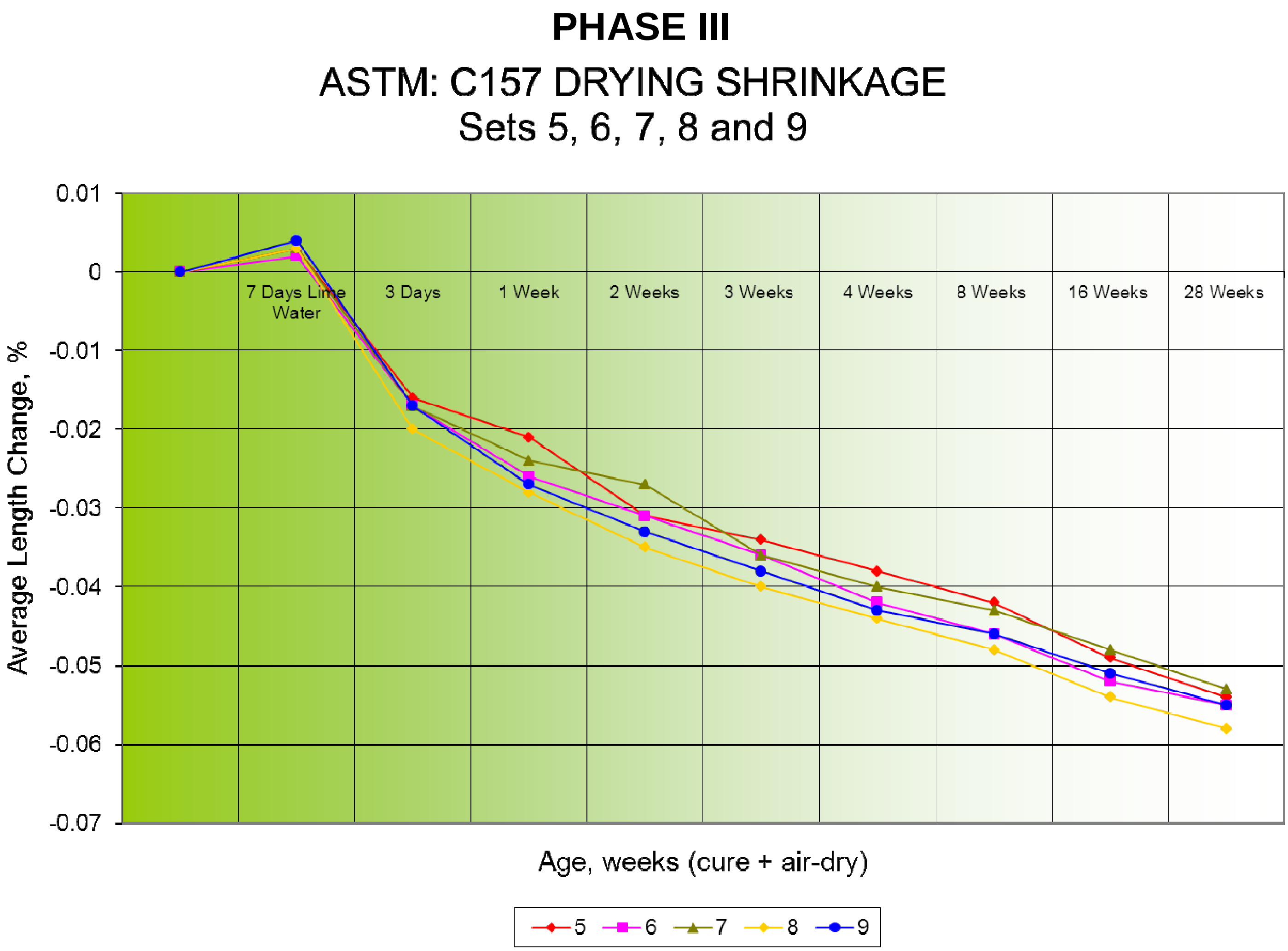
Table 2. Plastic Properties (Phase III)

	1 PC	2 30S	3 30FA	4 30S, 1MS	5 30S, 3MS	6 30CA, 3MS	7 1MS, 20S, 20FA	8 1MS, 20S, 20CA	9 3MS, 20S, 20CA
% Micro Silica	0	0	0	1	3	3	1	1	3
% Slag	0	30	0	30	30	0	20	20	20
% Fly Ash	0	0	30	0	0	30	20	20	20
Portland I/II (lbs)	658	461	461	454	441	441	388	388	375
Micro Silica (lbs)	0	0	0	6.6	19.7	19.7	6.6	6.6	19.7
Slag (lbs)	0	197.4	0	197.4	0	0	131.6	131.6	131.6
Fly Ash (lbs)	0	0	197.4	0	0	197.4	131.6	131.6	131.6
Total Cementitious (lbs)	658	658	658	658	658	658	658	658	658
Well Graded Aggregates (lbs)	3111	3111	3111	3111	3111	3111	3111	3111	3111
WRA (High Range) (cwt)	5.3	5.0	4.8	5.1	4.7	5.0	4.7	4.7	5.0
Corrosion Inhibitor (gal)	3	3	3	3	3	3	3	3	3
Total Water	263	263	263	263	263	263	263	263	263
W/C	0.4	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	1.2	1.1	1.1	1.2
Test Results									
Slump (in)	6.5	6.25	8.0	6.5	5.5	6.5	6.5	7.5	7.5
Air Content (%)	4.0	5.0	4.4	7.0	5.9	6.0	5.9	5.5	5.9
Unit Weight (lb/ft3)	147.6	147.2	147.8	145.9	146.8	147.0	147.1	146.8	146.8
Initial Set (hr:min)	3:20	3:25	4:40	3:20	3:20	4:20	3:50	3:55	4:05

The test results were relatively consistent and generally similar to the laboratory study. As to be expected with alternate cementitious materials, the study confirmed somewhat extended set times in comparison to a straight Portland cement mix (control mix). Yet, Mixes 7, 8 and 9, which were quaternary mixes, exhibited results in a fairly workable range. Furthermore, Mixes 2, 4 and 5 essentially matched the initial set of the Portland cement control mix. Of interest, these three mixes all contained 30% slag.

Drying Shrinkage Results

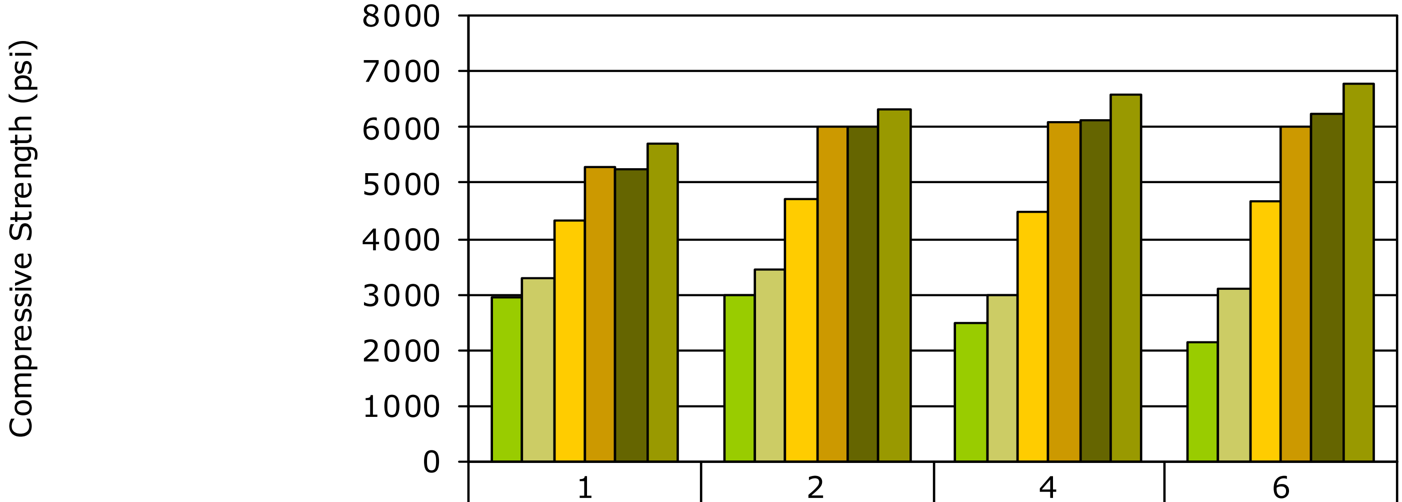
The drying shrinkage results of Mixes 5 through 9 are illustrated below. All of these tests were relatively consistent, and generally comparable to the control mix. It is the opinion of the committee that the results confirm the quality (controlled volume and uniform grading) of the paste serves to minimize shrinkage and results in low shrinkage concrete.



Compressive Strength Results

The graph below indicates four of the eight supplemental mixes had comparable twenty eight day strengths to the control mix. Of equal importance, several of the mixes had sufficient strength gain during early age for use in post-tensioned applications. Mixes 7, 8 and 9 had a higher total replacement percentage and used three different materials as a replacement for Portland cement; but performed well in terms of total and early strength gain.

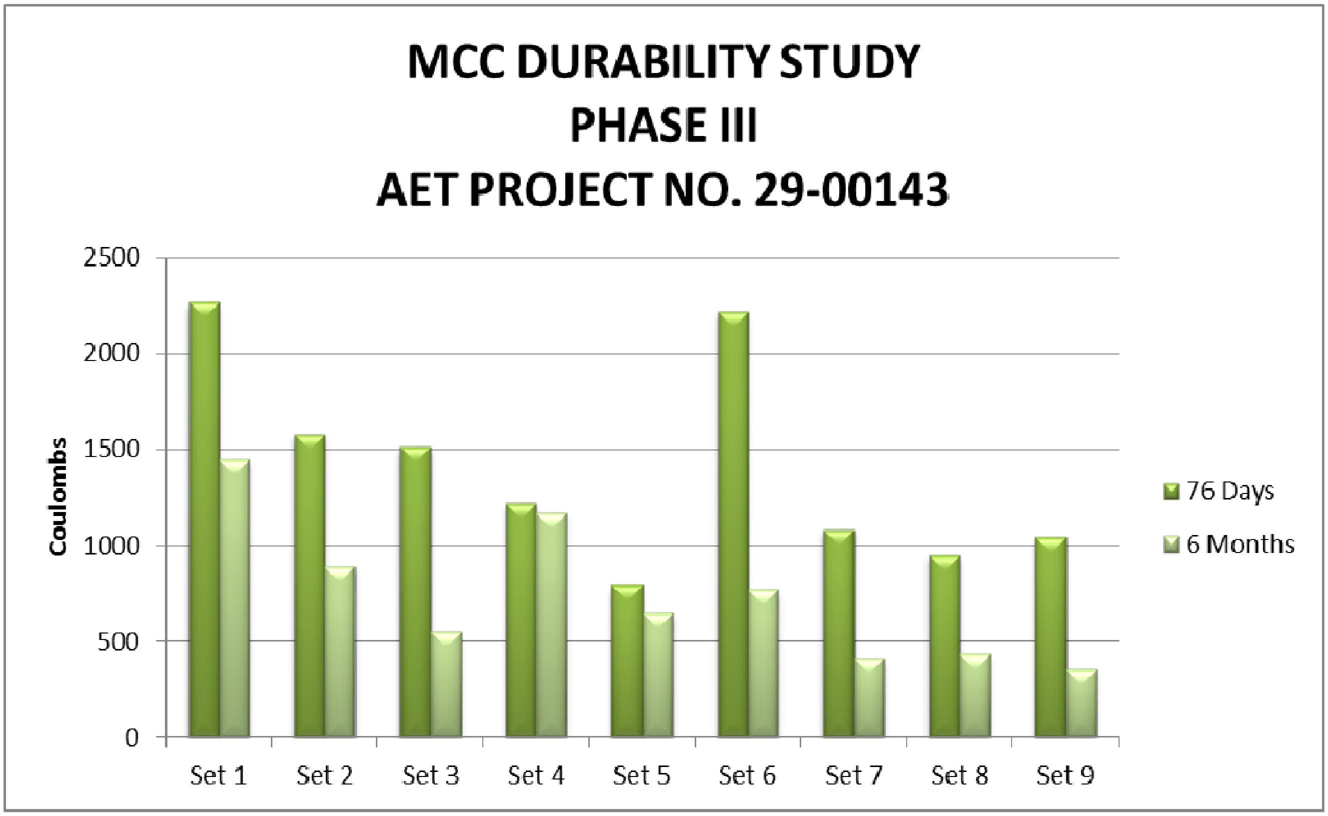
AVERAGE COMPRESSIVE STRENGTH (PSI)
FIELD (PHASE III)



	1	2	4	6
1 Day Cast Cylinders	2930	2990	2480	2150
2 Days Cast Cylinders	3290	3440	2970	3100
7 Days Cast Cylinders	4310	4700	4480	4680
28 Days Cast Cylinders	5270	6020	6070	6020
78 Days Cores	5240	6000	6130	6220
5 Years Cores	5700	6310	6580	6780

Mix Design

The seventy-six and six month rapid chloride permeability (RCP) results for Phase III are shown in the graph below. The results reveal the decrease in coulombs (i.e., lower permeability) with the use of SCM's.



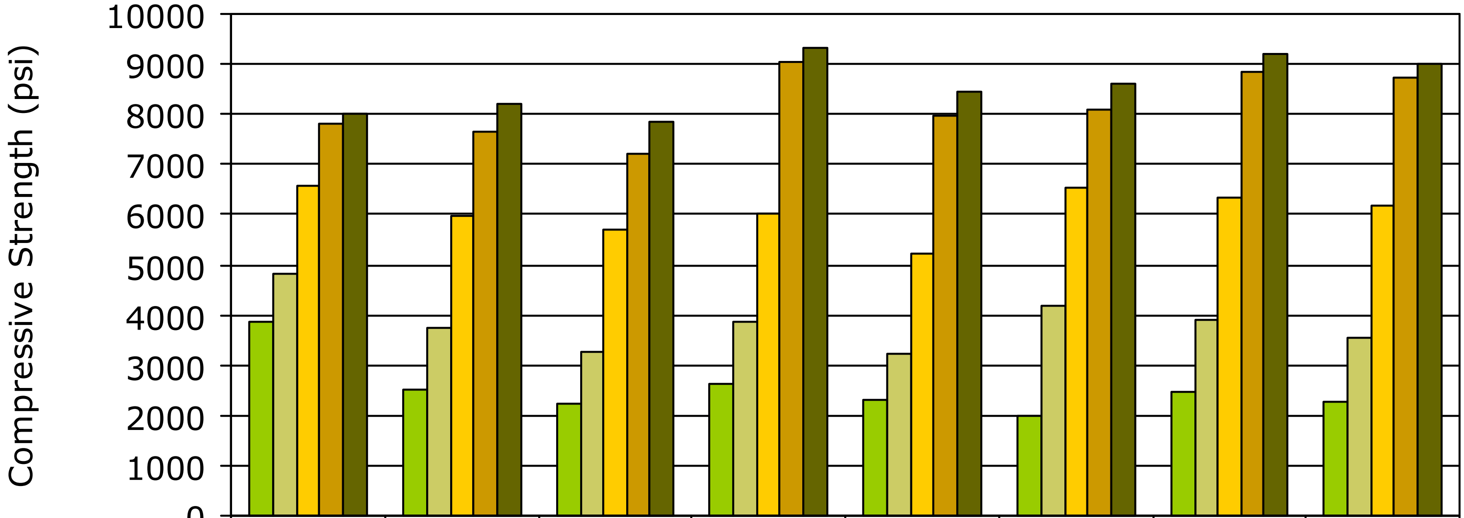
7 CONCRETE LIVES ON

Six hundred cubic yards of concrete was placed at three locations in the Twin Cities area. The three placements were all outdoors and represented three levels of use. The three levels being foot traffic, light vehicle traffic, and heavy truck traffic. The concrete placements provided the MCC with the connection from the original study to future long-term study.

Eight of the original nineteen laboratory mix designs were placed in a patio subjected to light foot traffic. The research team returned to the placement site five years later and cored two cores per mix design. The five year compressive strength gain is shown on the graph below.

The Phase III slab at AVR supplies us with the greatest potential for continuing this study. The test parameters indicated that the mix designs matched up well with the laboratory study. We look forward to obtaining long-term data from this field placement.

Average Compressive Strength (psi)
5 Year Strength Gain
Original Laboratory Study (Phase I)

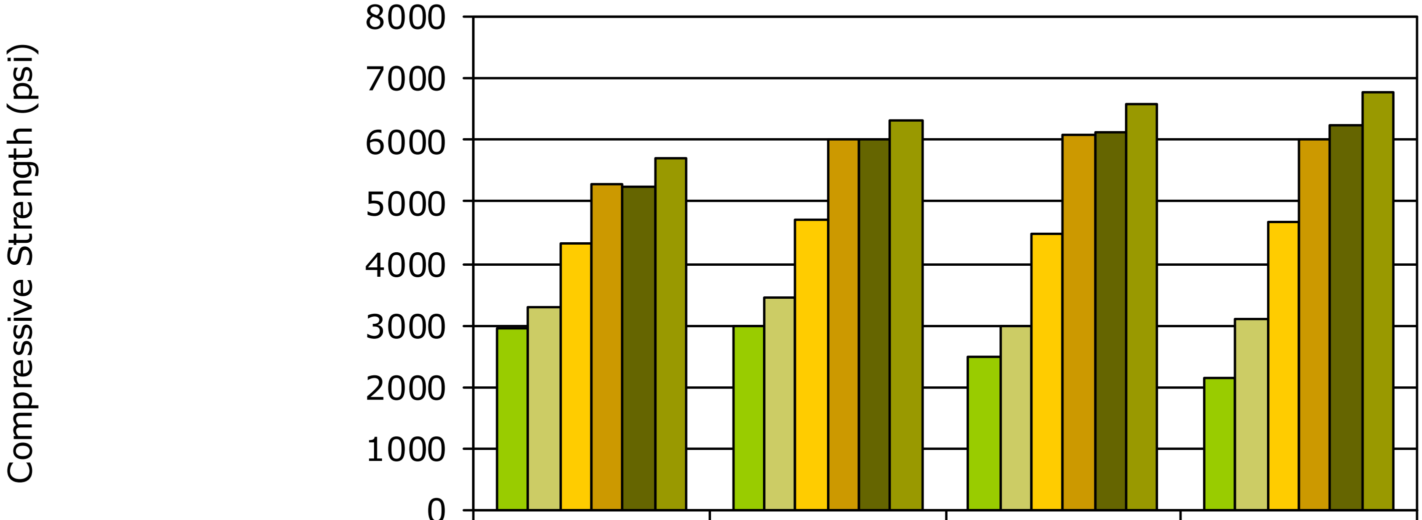


	1	2	3	6	7	11	12	16
1 Day	3870	2495	2240	2635	2300	1995	2470	2290
2 Days	4810	3740	3250	3845	3210	4165	3885	3565
7 Days	6580	5970	5710	6000	5200	6530	6325	6195
28 Days	7820	7650	7230	9040	7980	8093	8825	8735
5 Years	7990	8190	7860	9330	8430	8620	9210	9000

Mix Design

The research team went back to the Local 633 Training Center and took two cores from the pavements containing Mixes #1, 2, 4, and 6. The five year strength data can be seen in the graph below.

Average Compressive Strength (psi)
5 Year Strength Gain
Local 633 Training Center (Phase II)



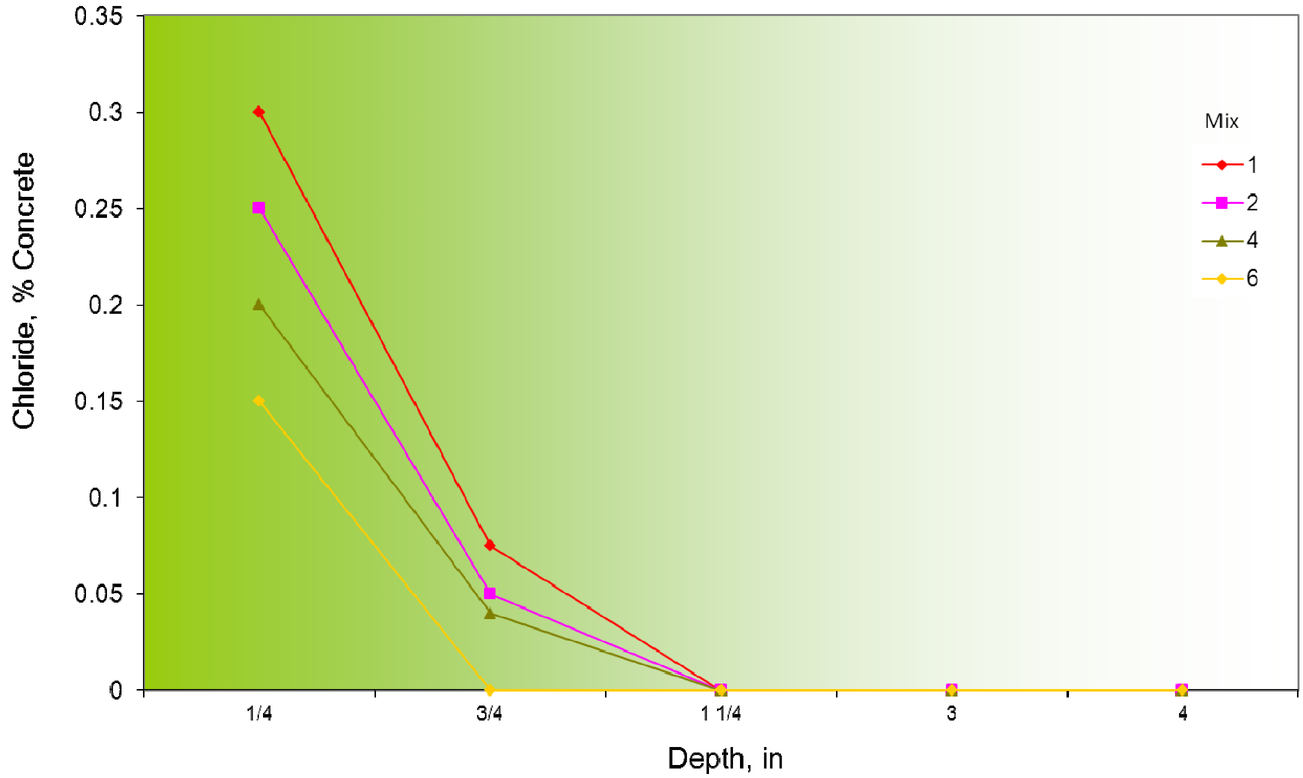
	1	2	4	6
1 Day Cast Cylinders	2930	2990	2480	2150
2 Days Cast Cylinders	3290	3440	2970	3100
7 Days Cast Cylinders	4310	4700	4480	4680
28 Days Cast Cylinders	5270	6020	6070	6020
78 Days Cores	5240	6000	6130	6220
5 Years Cores	5700	6310	6580	6780

Mix Design

The figure below shows chloride profiles (total acid-soluble) for five year old concrete specimens for Mixes #1, 2, 4, and 6 from Phase II. Even at these early ages the impact of SCM can be seen on the chloride profile, significantly increasing the resistance of the concrete to chloride penetration.

Although there is no single value that represents the chloride threshold content to initiate corrosion, values in the range of 0.05 to 0.10% are typically used. The Phase II chloride-ion profile indicates that the chloride-ion sampling should occur every 5 years for each of the remaining field slabs.

Chloride Profile
JATC Local 633 (Phase II)



8 SUMMARY

The study that MCC initiated in 2006 will provide valuable long-term data regarding the performance of concrete with SCM's. In particular, the team expects the incorporation of SCM's will lead to significant increases in the resistance to the chloride penetration. This study helped educate both the specifiers and the end-users for the increased use of SCM's. The study incorporated a wide variety of MCC members, from mix design specialists to concrete finishers. The group provided leading edge research in the field as well as the laboratory.

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