Evaluation of Chloride Limits for Reinforced Concrete Phase A

FINAL REPORT TO THE RMC RESEARCH & EDUCATION FOUNDATION (PROJECT 14-01); AND CONCRETE RESEARCH COUNCIL, ACI CONCRETE FOUNDATION

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INTRODUCTION

The corrosion of steel reinforcement in concrete is a major cause of deterioration to concrete structures. Corrosion of steel results in the formation of rust that occupies a larger volume than the original steel and causes staining, cracking, and spalling of the cover concrete. The highly alkaline environment in concrete protects steel from corrosion. However, when chlorides in solution reach the reinforcement, corrosion initiates and propagates damage. Chloride ions present in deicing chemicals and seawater are the primary source of external chlorides that can migrate to the reinforcing steel in concrete to cause corrosion of steel in concrete. Depending on the cover and quality of concrete, it can take a period of time before external chlorides reach a certain level of concentration (threshold) adequate to initiate corrosion at the level of the reinforcement. In contrast, internal chlorides are available to initiate corrosion when concrete is cast. Internal chlorides in concrete mixtures originate from concrete-making materials when concrete is produced. The scope of this study is on the internal chlorides in concrete. The ACI 318 Building Code Requirements for Structural Concrete establishes limits on water-soluble chloride ions in concrete mixtures used for reinforced and prestressed concrete based on assigned exposure class of structural members under the durability provisions. The chloride limits in ACI 318 are provided in Table 1.

ACI 318 requires that the water-soluble chloride content be determined in accordance with ASTM C1218 at an age between 28 and 42 days. Aging the specimens permits chlorides to be imbibed by hydration products and thereby measures the chloride ions in solution that can initiate corrosion. Currently, concrete producers must demonstrate that the concrete mixture submitted complies with the ACI 318 chloride limit by conducting the water-soluble chloride test. If the test results exceed the criteria, the test is typically repeated after changing one or more of the ingredient materials. If concrete had been placed prior to the availability of the chloride test results it may call into question the concrete that has been placed. The variability of ASTM C1218 can also cause a test result to exceed the limit.

The total chloride content in a concrete mixture can be estimated when the mixture proportions are being developed for the project. This involves calculating the total chloride content based on measured chloride content of the materials and the concrete mixture proportions. If the calculated total chloride content is less than the specified limit, there is good assurance that the water-soluble chloride measured on hardened concrete will comply and this testing may be avoided. Alternatively, if a correlation is established, either as a general relationship or specific to the proposed mixture, between total calculated chlorides and measured water-soluble chlorides, then concrete mixtures can be proportioned to ensure that the Code requirements will be met. The information can be included in the mixture submittal documents to the design professional for review and approval. Testing chloride content of hardened concrete may be waived by the design professional. A Code change proposal, if approved, will permit this alternative in ACI 318. This can avoid unnecessary time and costs to the project.

It is well established that supplementary cementitious materials (SCMs) such as slag cement, fly ash and silica fume, provide significant benefits to strength, durability and service life of concrete structures. Their use also has a societal impact whereby material that would be potentially diverted to landfills is put to beneficial use. Chloride limits in the ACI 318 Building Code are currently stated as percent by weight of portland cement as opposed to cementitious materials. This penalizes concrete mixtures containing SCMs as the limits are factored down by the quantity of SCMs in the mixture. This subsequently restricts the quantity of SCMs that can be used for optimum performance and sustainability.

The current ACI 318 Building Code chloride limits are based on research in the 1980s with primarily portland cement mixtures. These are conservative limits to ensure that the available chlorides in concrete will not exceed the threshold chloride concentration that can initiate corrosion. ACI 222R recommends more conservative chloride limits than those in ACI 318. There is no clear agreement on the actual chloride threshold concentration that initiates corrosion and there is additional uncertainty for mixtures that contain SCMs. In general, the threshold concentration is assumed to be between 2 to 4 lbs per cubic yard (0.05 to 0.1% by mass of concrete). It is useful to evaluate whether the ACI 318 Building Code chloride limits are appropriate for the different exposure classes of Exposure Category C and for different concrete mixtures that contain SCMs.

This project was conceptualized to be performed in two phases.

The objective of Phase A is to establish a relationship between total chlorides calculated from the concrete materials and water-soluble chlorides measured on concrete specimens at a test age between 28 and 42 days. This information is useful by itself for concrete producers to use and is necessary information for mixtures that will be evaluated in Phase B.

The objectives of Phase B are:

1. Propose chloride limits on the basis of total cementitious materials; and
2. Evaluate the validity of current chloride limits for reinforced concrete stated in ACI 318.

This report summarizes the findings in Phase A of the project.

MATERIALS AND MIXTURE PROPORTIONS

The following materials were used for the concrete mixtures:

- ASTM C150 Type II portland cement (II) with C_3A = 6.6% (Bogue)/4.0% (QXRD)*
- ASTM C150 Type V portland cement (V) with C_3A = 2.9% (Bogue)/2.6% (QXRD)
- ASTM C989 slag cement (SL)
- ASTM C618 Class F fly ash (FF)
- ASTM C618 Class C fly ash (CF)
- ASTM C1240 silica fume (SF)
- ASTM C33 No. 57 crushed coarse aggregate
- ASTM C33 No. 57 crushed coarse aggregate with high chloride from Illinois (IL)
- ASTM C33 natural sand with an FM=2.83
- ASTM C494 Type F high-range water-reducing admixture
- Powdered Calcium chloride (97.1% purity)

* C_3A calculated from Bogue equations is relevant to ASTM C150. The cement supplier also reported the C_3A from direct phase determination by quantitative X-ray diffraction (QXRD) using the Rietveld method.

Table 2 summarizes the chemical characteristics of the cementitious materials used in this project as reported by the supplier. The measured chloride content of the materials used for the concrete mixtures are reported in Table 3. The acid-soluble and water-soluble chloride contents of the different material ingredients were measured by ASTM C1152 and ASTM C1218, respectively.

The mixture variables considered for Phase A of this study are summarized below and in Table 4:

- w/cm of 0.40 and 0.50;
- C_3A content of portland cement of 6.6% and 2.9%;
- Class F fly ash at 25% and 50% by weight of cementitious materials;
- Class C fly ash at 25% by weight of cementitious materials;
- Slag cement at 40% by weight of cementitious materials;
- Silica fume at 6% by weight of cementitious materials; and
- Coarse aggregate containing chlorides.

The C_3A phase is known to imbibe chlorides when it hydrates and for that purpose portland cement with low and high C_3A content was used.

Concrete mixtures were non-air-entrained. The mixture proportions, fresh concrete properties, and compressive strength of the mixtures are provided in Tables 4a and 4b for the high C_3A and low C_3A cement mixtures, respectively. Calculated batch quantities are based on quantities used for each batch and the measured density of fresh concrete. Mixture designations were assigned by the w/cm followed by the SCM type and quantity. Mixtures without SCM use the designation “PC”. Mixtures with low C_3A cement (Type V) had the suffix V and mixtures with high C_3A cement (Type II) had the suffix II. For example, 0.40FF25-II refers to mixture with a w/cm of 0.40 and 25% Class F fly ash with a Type II cement. A Type F high-range water-reducing admixture (HRWRA) was added as needed to produce a slump in the range of 2 to 8 in.

EXPERIMENTAL PROCEDURES

All concrete mixing, testing, and specimen preparation was done at the NRMCA research laboratory. Concrete mixtures were mixed in a revolving drum laboratory mixer in accordance with ASTM C192. Fresh concrete was tested for slump (C143), temperature (C1064), air content by the pressure method (C231), and density (C138). The gravimetric air content was calculated in accordance with ASTM C138. On completion of mixing, concrete was removed to cast one 4x8 in. cylinder. The weight of the cylinder was measured. This cylinder was used for measuring the background chloride level of the concrete mixture. Chloride in the form of powdered calcium chloride was added to the remaining concrete so that the added chloride was equal to 0.15% of the cementitious materials. The concrete was mixed for two minutes to incorporate the added chlorides into the mixture. Subsequent chloride additions were based on the decreased volume in the mixer after the concrete was removed for molding specimens. Further incremental chloride additions were such that the added chloride contents of subsequent specimens were 0.30, 1.0 and 2.0% of the cementitious materials. After the last chloride addition, fresh concrete properties were measured and two 4x8 in. cylindrical specimens were cast and standard cured to an age of 28 days for compressive strength measurement.

Chloride measurement on hardened concrete was performed between 28 and 42 days from the time of casting, and specimens were placed in a moist room conforming to ASTM C511 for the duration between casting and testing. Chloride content measurements were conducted at Tourney (TCG) and NRMCA labs. One concrete cylinder at each added chloride content was sectioned. After discarding the top 1 in. of concrete, chloride contents were analyzed by both laboratories from subsequent 2 in. thick sections of the same cylinder. One 2 in. slice of concrete was cut and sent to TCG from each specimen. Each 2 in. slice was shrink-wrapped and secured with a rubber band. Mixtures batched on the same day were grouped in a sealed bag before being placed in a container with pre-soaked burlap. Shipments were made between 19 and 22 days after casting. TCG measured chloride content on all the specimens. NRMCA measured chloride content on about 25% of the samples. These replicate measurements between TCG and NRMCA provide a measure of the multi-laboratory variation for this study.

The acid-soluble and water-soluble chloride contents of the different concrete mixtures were measured by ASTM C1152 and ASTM C1218, respectively. The measured acid-soluble chloride content is used as an estimate of the total chlorides in the mixture. This result is also used to compare to the calculated total chloride content of the mixture. Water-soluble chloride contents were measured on the background concrete without admixed chlorides, 0.15%, 0.3%, 1.0%, and 2.0% chloride level for each mixture. Acid-soluble chloride contents were measured on the 0.15%, 1.0%, and 2.0% chloride levels only. TCG measured the acid-soluble chloride content on the background concrete (no added chlorides) level for some of the mixtures. Two chloride measurements were made for each chloride level. The reported chloride content is the average of two measurements. TCG conducted 360 chloride measurements while NRMCA conducted 96 chloride measurements. In addition, TCG conducted 72 chloride measurements at one year to see if longer term caused any change in the chloride measurements. Comparisons of results between the two laboratories were within the precision of the ASTM test methods, with some exceptions.

EXPERIMENTAL RESULTS

The calculated total chloride contents of the various mixtures are reported in Table 6. This is reported both in terms of percent by mass of concrete and percent by mass of cementitious materials.

The measured acid-soluble chloride content, expressed as percent by mass of concrete, is reported in Table 7. The ratio of the measured acid-soluble chloride to the calculated total chloride content of the mixtures is reported in Table 8. For most of the mixtures, this ratio is close to 1, indicating that the calculated chloride content is reasonably consistent with the measured total chloride. The measured acid-soluble-to-calculated total chloride content ratio for 17 out of the 22 mixtures was greater than 1 for the 0.15% added chloride condition. For the 1% and 2% chloride additions, the average measured acid-soluble-to-calculated total chloride content ratio was clearly lower than 1 indicating that either the chlorides were tightly bound in the hydration products, or the testing technique was inadequate at such high chloride contents, or the difference may be attributed to errors with chloride addition to the portion of the mixture or with the measurements. The measured water-soluble chloride content of the concrete mixtures, expressed as percent by mass of concrete, is reported in Table 9. These data are expressed as percent by mass of cementitious materials in Table 10. The data in Table 10 provides a basis to compare the measured result required in ACI 318 relative to the calculated total chloride content in the concrete mixtures. The ratio of the measured water-soluble chloride content to the calculated total chloride content is reported in Table 11. The ratio reported in Table 11 for all mixtures is less than 1. This indicates chlorides are bound as a result of hydration of cement and are not available in the pore solution to influence the corrosion of reinforcement. This also supports the premise that if the calculated total chloride of the concrete mixture is equal to or less than the chloride limit in the Code, the measured water-soluble chlorides determined on hardened concrete at an age between 28 and 42 days will comply with the limit. This is true regardless of cementitious material and, in this case, the aggregates used in the concrete mixture.

Table 12 reports the ratio of the measured water-soluble chlorides to measured acid-soluble chlorides. The measured acid-soluble chlorides will include those that are bound within the hydration products. The ratios in Table 12, as might be expected, are also less than 1 for all mixtures. A lower ratio is indicative of higher chloride binding by the cementitious materials.

As the added chloride contents of concrete mixtures increased from 0.15% to 1%, the average ratio for all mixtures measured by TCG increased from 0.52 to 0.72, which is indicative of reduced chloride binding relative to the added amount. The ratio for the mixtures at 2% added chloride was about the same as that for mixtures with 1% added chloride. While the ratio remains constant at higher chloride content, the quantity of bound chlorides does increase because of the higher total chlorides in the mixture. The mixtures with the coarse aggregates with a higher acid-soluble chloride content (IL) had ratios of measured acid-soluble-to-calculated total chloride content similar to the corresponding mixtures with the trap rock coarse aggregate. This is reported in Table 8. However, for the mixtures with the IL aggregate, the ratio of the measured water-soluble to calculated total chloride content ratios were lower than the corresponding mixtures with the trap rock coarse aggregate as can be seen in Table 11.

Comparisons of the results for acid-soluble and water-soluble chlorides between TCG and NRMCA are shown in Figures 1a and 1b, respectively, for the 0.15% chloride level. Overall, the difference in the results are within the acceptable range (d2s) for multi-laboratory precision in ASTM C 1152. For five out of the 22 mixtures the NRMCA measured water-soluble chloride contents were close to or just above the upper limit of acceptable range between labs. The water-soluble chloride contents over the 22 mixtures measured by NRMCA was on average 19% higher than that measured by TCG. The subsequent figures and discussion uses the TCG measurements for comparisons.

Cement with higher C_3A are considered to have a higher binding capacity for chlorides that ingress from external sources (1, 2). Figure 2 plots the ratio of measured water-soluble to acid-soluble results for mixtures that used Type II (higher C_3A) compared to mixtures with Type V (lower C_3A) cement. No significant differences of chloride binding can be attributed to the types of portland cement used in this study. Ratio for individual mixtures are in Table 12. For the two mixtures without SCMs, the average ratio is marginally lower for the Type V cement compared to the Type II cement. In Figure 2, for the 0.15% added chloride level, on average the ratio for mixtures with Type II cement is higher than the average of mixtures with Type V cement. This indicates that there is a difference in binding of chloride that is admixed versus chloride that permeates the concrete from the environment. For the 1% and 2% chloride levels, the average ratio of water-to-acid-soluble chloride is higher and essentially similar for both cement types. The increase in ratio of water to acid-soluble chloride, at higher chloride levels is observed for chloride ingress into hardened concrete (3, 4).

Figure 3 illustrates the effect of w/cm on the ratio of measured water-soluble to acid-soluble chlorides. for the 0.15% chloride level. As the w/cm decreased from 0.50 to 0.40, the ratio decreased from 0.56 to 0.50 for the portland cement mixtures. The other comparisons are shown in Figure 3 where differences due to w/cm are not significantly different. In Table 12, for mixtures at the 1% and 2% chloride levels no significant differences in the ratio due to mixture w/cm can be discerned.

Figure 4a-c shows the influence of SCMs on the ratio of the measured water-soluble-to-acid-soluble chloride content for the mixtures with 0.15%, 1% and 2% chloride levels, respectively. While there are some differences, on average the ratios for the mixtures with SCMs are similar to that of the corresponding PC mixtures. There was no discernible difference for these ratios between the different SCMs used. One possible difference might be for the mixture containing 50% Class F fly ash where the ratio is higher suggesting lower chloride binding. However, this might be due to the time effect related to the reactivity of the higher volume of fly ash at the tested age.

Figure 5 and Table 11 show the ratio of the measured water-soluble to calculated total chloride content ratio for all 22 mixtures tested at all chloride levels. These data include the measurements by NRMCA. The maximum ratio from TCG measurements was 0.83 for the 0.40FF50-V mixture at the 1% chloride level. The maximum ratio from the NRMCA data was 0.94 for the 0.50FF25-V mixture at the 0.15% chloride level. Note that the actual ratios varied between 0.38 and 0.94 for the mixtures that had added chlorides. Since all the ratios are less than 1.0, it supports the proposal to permit calculation of total chlorides estimated from the materials and mixture proportions. The calculated chloride content is a conservative estimate of the water-soluble chloride content that is the basis for the limits in the Building Code. For mixtures with no added chlorides, the maximum ratio was 0.52 with a range of 0.21 to 0.52. In this case, multiplying the calculated total chlorides by a factor of 0.6 would provide a conservative estimate of the water-soluble chloride content that would be measured on the concrete mixture. This would avoid the measurement of water-soluble chlorides in hardened concrete as currently required by ACI 318.

Table 13 reports the one year measured chloride test results for selected mixtures. Also indicated is the percent change relative to the measured results at an age between 28 and 42 days. Out of the 36 measurements at one year, the measured chloride content was within 10% for 24 results; for 11 cases the measured chlorides were more than 10% lower at one year; only one measurement was more than 10% higher.

CONCLUSIONS AND NEXT STEPS

The measured acid-soluble, water-soluble chloride contents and the calculated total chloride contents were determined for a range of concrete mixtures consisting of different SCMs, portland cement C_3A content, w/cm, and aggregate types. The test data showed that:

- The calculated total chloride contents of concrete mixtures were reasonably consistent with the measured acid-soluble chloride content.
- The ratio of the measured water-soluble chloride-to-calculated total chloride content was less than one which is as expected due to chloride binding in hydration products. A higher ratio was observed with increased chloride addition but this ratio was relatively constant when chloride content exceeded 1% by weight of cementitious materials.
- A lower ratio of measured water-soluble to acid-soluble chloride contents suggests a greater amount of bound chloride. The results in this study suggest that there is no significant difference in the bound chloride content in mixtures depending on type of portland cement, w/cm (0.40 and 0.50), and type and quantity of SCM used.
- The ratio of the measured water-soluble chloride to the calculated total chloride content was less than 1.0 for all mixtures. This supports the proposal that if the calculated total chloride content of concrete mixtures is less than the water-soluble chloride limits in the Building Code, it will be deemed to comply with the Code requirements on chloride limits based on measurement of water-soluble chlorides on hardened concrete.
- The results show that, in the case where no chlorides have been added, the calculated total chloride content from materials and mixture proportions can be multiplied by 0.6 to get a conservative estimate of the water-soluble chloride content. In the case where chlorides have been added intentionally, the calculated chloride content can be a conservative estimate of the water-soluble chloride content.
- The ratio of the measured water-soluble chloride-to-calculated total chloride content of mixtures made with aggregates with a high acid-soluble chloride content were lower than that of corresponding mixtures prepared with the trap rock aggregate.
- The one year measured chloride test results were similar to the early age test results. This suggests that no significant change in chloride binding occurred between the early age measurement and one year.
- The effect of C_3A content on chloride binding measured for admixed chlorides in this study appears to be different from that of ingressed chlorides.

The next phase of this project (Phase B) will require proportioning mixtures with different levels of chloride contents and conducting corrosion tests on the specimens prepared from those mixtures. The results obtained in this phase can be used to establish mixture proportions of concretes in Phase B.

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Table 1 Chloride Limits for Concrete as required by ACI 318 Building Code for Structural Concrete

Exposure Class	Max w/cm	Min f'_c	Maximum water soluble chloride ion content in concrete, percent by weight of cement#	
			Reinforced Concrete	Prestressed Concrete
C0 – Concrete dry or protected from moisture	N/A	2500	1.00	0.06
C1 - Concrete exposed to moisture but not to external sources of chlorides	N/A	2500	0.30	0.06
C2 - Concrete exposed to moisture and an external source of chlorides	0.40	5000	0.15	0.06

#Water-soluble chloride ion content that is contributed from the ingredients including water, aggregates, cementitious materials, and admixtures shall be determined on the concrete mixture by ASTM C1218 at age between 28 and 42 days.

Table 2 Chemical Characteristics of cementitious materials

Material	Type II	Type V	Slag Cement	Class F Fly Ash	Class C Fly Ash	Silica Fume
Designation	II	V	SL	FF	CF	SF
Silicon oxide (SiO_2), %	19.7	21.3	-	48.6	37.2	85.2
Aluminum oxide (Al_2O_3), %	4.6	3.6		24.1	21.6	0.2
Iron oxide (Fe_2O_3), %	3.3	3.8	-	16.6	5.7	2.5
Calcium oxide (CaO), %	62.4	64.0	-	4.0	23.4	0.7
Magnesium oxide (MgO), %	3.0	1.7	-	1.2	4.2	6.6
Sulfur trioxide (SO_3), %	2.8	2.7		0.8	1.4	0.3
Loss of Ignition, %	2.9	2.0	-	1.4	0.2	4.03
Relative Density			2.93	2.38	2.64	2.26
Total Alkali (as Na_2O eq), %	0.55	0.58		1.72	1.97	0.66
Tricalcium Silicate (C_3S), %	55.6	61.8	-	-	-	-
Dicalcium silicate (C_2S), %	19.7	14.3	-	-	-	-
Tricalcium Aluminate (C_3A), %	6.6	3.2	-	-	-	-
Tetracalcium Aluminoferrite (C_4AF), %	10.3	11.4	-	-	-	-

Table 3 Measured Chloride Contents of Materials

Material	Acid-soluble chloride (C1152), %	Water-soluble chloride (C1218), %
Type II Cement	0.0108	B
Type V Cement	0.0068	B
Slag Cement	0.0251	B
Class F Fly Ash	0.0032	B
Class C Fly Ash	0.0078	B
Silica Fume	0.0714	B
No. 57 crushed coarse aggregate	0.0124	0.0041
No. 57 crushed coarse aggregate (IL)	0.0664	0.0184
Natural Sand	0.0011	0.0012
Type F HRWRA	A	0.007
city water	A	0.005

[A] - Not applicable for liquids

[B] - Acid-soluble chlorides are relevant for cementitious materials

Table 4 Concrete Mixture Variables

Mix ID	Cement Type	w/cm	SCM (%)
0.50FF25-II	II	0.50	FF (25)
0.50CF25-II			CF (25)
0.50SL40-II			SL (40)
0.40FF25-II		0.40	FF (25)
0.40CF25-II			CF (25)
0.40SL40-II			SL (40)
0.40SF6-II			SF (6)
0.40FF50-II			FF (50)
0.50FF25-V	V	0.50	FF (25)
0.50CF25-V			CF (25)
0.50SL40-V			SL (40)
0.40FF25-V		0.40	FF (25)
0.40CF25-V			CF (25)
0.40SL40-V			SL (40)
0.40SF6-V			SF (6)
0.40FF50-V			FF (50)
0.50PC-II	II	0.50	
0.40PC-II		0.40	
0.50PC-V	V	0.50	
0.40PC-V		0.40	
0.50PC-II-IL#	II	0.50	
0.50PC-V-IL#	V	0.50	

Coarse aggregate with the high chloride content (IL) was used. The traprock coarse aggregate was used in the other mixtures

Table 5a Mixture Proportions, Fresh Concrete Properties and Compressive Strength of mixtures with Type II (high C_3A)

Mixture Designation	0.50FF25-II	0.50CF25-II	0.50SL40-II	0.40FF25-II	0.40CF25-II	0.40SL40-II	0.40SF6-II	0.40FF50-II	0.50PC-II	0.40PC-II	0.50PC-II-IL
Calculated Batch Quantities											
Total Cementitious	552	551	550	629	632	633	630	626	547	633	544
Type II Portland cement, lb/yd^3	414	413	330	472	474	380	592	313	547	633	544
Slag, lb/yd^3			220			253					
Class F Fly ash, lb/yd^3	138			157				313			
Class C Fly ash, lb/yd^3		138			158						
Silica Fume, lb/yd^3							38				
Supplementary cement, %	25	25	0	25	25	0	6	50	0	0	0
No.57 Coarse Agg., lb/yd^3	1847	1845	1842	1854	1861	1866	1856	1844	1831	1864	
No.57 Coarse Agg. (IL), lb/yd^3											1676
Fine Aggregate, lb/yd^3	1453	1467	1472	1457	1480	1493	1487	1407	1477	1507	1486
Mixing Water, lb/yd^3	276	276	275	252	252	253	252	250	273	253	272
w/cm	*0.50*	*0.50*	*0.50*	*0.40*	*0.40*	*0.40*	*0.40*	*0.40*	*0.50*	*0.40*	*0.50*
ASTM C494 Type F, oz/cwt	3.0	3.0	3.9	4.6	6.4	7.9	8.6	5.9	3.0	6.8	3.6
Fresh Concrete Properties											
ASTM C143, Slump, in.	6 3/4	5 1/2	3	2 1/4	4 1/2	5	2 1/4	6 3/4	4	2 1/4	4 3/4
ASTM C231, Air, %	3.0	3.3	3.3	2.3	2.5	2.0	2.5	3.0	3.5	2.6	3.2
ASTM C138, Density, lb/ft^3	152.9	153.3	153.3	155.3	156.5	157.3	156.5	152.9	152.9	157.7	147.3
ASTM C138, Gravimetric Air, %	1.7	1.8	2.0	1.3	1.0	0.7	1.2	1.8	2.6	0.8	3.1
ASTM C1064, Temperature, °F	75	75	75	75	75	75	75	75	75	75	75
ASTM C39, Compressive Strength, psi											
28d	5,150	6,420	7,720	8,020	8,970	11,000	10,550	4,840	6,320	9,940	7,050

Table 5b Mixture Proportions, Fresh Concrete Properties and Compressive Strength of Mixtures with Type V (low C_3A)

Mixture Designation	0.50FF25-V	0.50CF25-V	0.50SL40-V	0.40FF25-V	0.40CF25-V	0.40SL40-V	0.40SF6-V	0.40FF50-V	0.50PC-V	0.40PC-V	0.50PC-V-IL
Calculated Batch Quantities											
Total Cementitious	555	557	553	637	638	629	630	631	548	633	551
Type V Portland cement, lb/yd^3	416	418	332	478	479	377	592	315	548	633	551
Slag, lb/yd^3			221			251					
Class F Fly ash, lb/yd^3	139			159				315			
Class C Fly ash, lb/yd^3		139			160						
Silica Fume, lb/yd^3							38				
Supplementary cement, %	25	25	0	25	25	0	6	50	0	0	0
No.57 Coarse Agg., lb/yd^3	1857	1865	1851	1878	1880	1852	1856	1859	1836	1864	
No.57 Coarse Agg. (IL), lb/yd^3											1699
Fine Aggregate, lb/yd^3	1461	1482	1480	1476	1495	1482	1487	1418	1481	1507	1506
Mixing Water, lb/yd^3	277	278	276	255	255	251	252	252	274	253	275
w/cm	*0.50*	*0.50*	*0.50*	*0.40*	*0.40*	*0.40*	*0.40*	*0.40*	*0.50*	*0.40*	*0.50*
Sika Viscocrete 2100, oz/cwt	3.5	3.0	3.9	7.4	6.9	7.2	9.0	6.7	*3.47*	8.1	3.6
Fresh Concrete Properties											
ASTM C143, Slump, in.	4	2 1/2	2 1/4	4	2 3/4	4 1/4	2	8	2 1/2	2 1/4	3 1/2
ASTM C231, Air, %	2.7	2.6	3.0	1.9	2.2	2.4	2.5	2.5	3.4	2.5	2.7
ASTM C138, Density, lb/ft^3	153.7	154.9	154.1	157.3	158.1	156.1	156.5	154.1	153.3	157.7	149.3
ASTM C138, Gravimetric Air, %	1.2	0.8	1.5	0.2	0.1	1.4	1.2	1.1	2.3	0.8	1.8
ASTM C1064, Temperature, °F	75	75	75	75	75	75	75	75	75	75	75
ASTM C39, Compressive Strength, psi											
28d	5,390	7,300	7,870	8,790	10,800	10,700	11,150	5,520	7,430	11,020	7,510

Table 6 Calculated Total Chloride Content in Concrete Mixtures

Mixture Designation	Calculated Total Chloride, % Concrete					Calculated Total Chloride, % Cementitious				
	Background	0.15% Level	0.30% Level	1.0% Level	2.0% Level	Background	0.15% Level	0.30% Level	1.0% Level	2.0% Level
0.50FF25-II	0.008	0.028	0.049	0.147	0.286	0.056	0.212	0.369	1.010	2.144
0.50CF25-II	0.008	0.028	0.049	0.147	0.286	0.057	0.214	0.370	1.101	2.145
0.50SL40-II	0.008	0.029	0.050	0.147	0.286	0.064	0.220	0.377	1.107	2.151
0.40FF25-II	0.008	0.031	0.055	0.164	0.321	0.050	0.207	0.363	1.094	2.138
0.40CF25-II	0.008	0.031	0.054	0.164	0.320	0.051	0.208	0.364	1.095	2.139
0.40SL40-II	0.009	0.032	0.055	0.164	0.320	0.058	0.214	0.371	1.102	2.146
0.40SF6-II	0.008	0.032	0.055	0.164	0.319	0.056	0.212	0.369	1.010	2.144
0.40FF50-II	0.007	0.031	0.055	0.166	0.324	0.048	0.205	0.361	1.092	2.136
0.50FF25-V	0.007	0.028	0.049	0.147	0.286	0.053	0.209	0.366	1.097	2.141
0.50CF25-V	0.007	0.028	0.049	0.146	0.285	0.054	0.211	0.367	1.098	2.142
0.50SL40-V	0.008	0.029	0.050	0.147	0.286	0.061	0.218	0.374	1.105	2.149
0.40FF25-V	0.007	0.031	0.054	0.164	0.320	0.047	0.204	0.360	1.091	2.135
0.40CF25-V	0.007	0.031	0.054	0.163	0.319	0.048	0.205	0.361	1.092	2.136
0.40SL40-V	0.008	0.032	0.055	0.164	0.320	0.055	0.212	0.369	1.099	2.143
0.40SF6-V	0.008	0.031	0.054	0.163	0.319	0.052	0.208	0.365	1.096	2.140
0.40FF50-V	0.007	0.031	0.054	0.165	0.323	0.046	0.203	0.359	1.090	2.134
0.50PC-II	0.008	0.028	0.049	0.146	0.284	0.058	0.214	0.371	1.102	2.146
0.40PC-II	0.008	0.031	0.054	0.163	0.318	0.052	0.209	0.365	1.096	2.140
0.50PC-V	0.007	0.028	0.049	0.145	0.284	0.054	0.210	0.367	1.098	2.142
0.40PC-V	0.007	0.030	0.054	0.162	0.317	0.048	0.205	0.361	1.092	2.136
0.50PC-II-IL	0.030	0.052	0.073	0.173	0.315	0.221	0.378	0.534	1.265	2.309
0.50PC-V-IL	0.030	0.051	0.072	0.172	0.315	0.217	0.374	0.530	1.261	2.305

Table 7 Measured Acid-Soluble Chloride Content, ASTM C1152

Mixture Designation	Measured Acid-Soluble Chloride, % Concrete					
	Background	0.15% Level		1.0% Level		2.0% Level
		TCG	NRMCA	TCG	NRMCA	
0.50FF25-II	0.009	0.034	0.033	0.123	0.128	0.222
0.50CF25-II		0.027	0.034	0.133		0.247
0.50SL40-II		0.030	0.035	0.135		0.245
0.40FF25-II		0.031	0.032	0.161	0.153	0.283
0.40CF25-II		0.034	0.037	0.165		0.274
0.40SL40-II		0.033	0.036	0.162		0.290
0.40SF6-II		0.030	0.038	0.135		0.280
0.40FF50-II		0.036	0.036	0.155		0.262
0.50FF25-V	0.011	0.049	0.041	0.147		0.268
0.50CF25-V		0.032	0.036	0.144		0.245
0.50SL40-V		0.033	0.036	0.130		0.255
0.40FF25-V		0.033	0.033	0.161		0.272
0.40CF25-V		0.031	0.036	0.153		0.264
0.40SL40-V		0.031	0.036	0.154		0.276
0.40SF6-V		0.034	0.032	0.156		0.284
0.40FF50-V		0.033	0.033	0.175		0.245
0.50PC-II		0.028	0.032	0.127		0.206
0.40PC-II		0.034	0.034	0.164		0.278
0.50PC-V		0.025	0.030	0.126		0.230
0.40PC-V		0.032	0.034	0.155		0.259
0.50PC-II-IL	0.051	0.068	0.062	0.180		0.302
0.50PC-V-IL	0.031	0.060	0.062	0.169		0.276

Table 8 Ratio of Measured Acid-Soluble to Calculated Total Chloride Content

Mixture Designation	Measured Acid-Soluble to Calculated Total Chloride					
	Background	0.15% Level		1.0% Level		2.0% Level
		TCG	NRMCA	TCG	NRMCA	
0.50FF25-II	1.18	1.20	1.17	0.84	0.87	0.77
0.50CF25-II		0.93	1.20	0.91		0.86
0.50SL40-II		1.02	1.19	0.92		0.86
0.40FF25-II		1.00	1.04	0.98	0.93	0.88
0.40CF25-II		1.10	1.18	1.01		0.86
0.40SL40-II		1.03	1.11	0.99		0.91
0.40SF6-II		0.96	1.20	0.82		0.88
0.40FF50-II		1.15	1.15	0.94		0.81
0.50FF25-V	1.54	1.75	1.48	1.00		0.94
0.50CF25-V		1.14	1.27	0.99		0.86
0.50SL40-V		1.13	1.24	0.89		0.89
0.40FF25-V		1.08	1.08	0.98		0.85
0.40CF25-V		1.01	1.18	0.94		0.83
0.40SL40-V		0.98	1.13	0.94		0.86
0.40SF6-V		1.11	1.02	0.96		0.89
0.40FF50-V		1.06	1.07	1.06		0.76
0.50PC-II		0.99	1.13	0.87		0.72
0.40PC-II		1.09	1.09	1.01		0.87
0.50PC-V		0.89	1.09	0.86		0.81
0.40PC-V		1.05	1.12	0.96		0.82
0.50PC-II-IL	1.67	1.32	1.21	1.04		0.96
0.50PC-V-IL	1.03	1.18	1.21	0.98		0.88
Average	1.36	1.10	1.16	0.96		0.85

Table 9 ASTM C1218 - Measured Water-Soluble Chloride Content, % concrete

Mixture Designation	Measured Water-Soluble Chloride, % Concrete						
	Background	0.15% Level		0.30% Level	1.0% Level		2.0% Level
		TCG	NRMCA		TCG	NRMCA	
0.50FF25-II	0.003	0.019	0.019	0.038	0.092	0.099	0.171
0.50CF25-II	0.003	0.015	0.026	0.030	0.086		0.172
0.50SL40-II	0.004	0.017	0.025	0.033	0.094		0.165
0.40FF25-II	0.003	0.018	0.020	0.035	0.115	0.118	0.219
0.40CF25-II	0.004	0.019	0.019	0.035	0.110		0.212
0.40SL40-II	0.004	0.019	0.020	0.038	0.111		0.210
0.40SF6-II	0.003	0.016	0.017	0.036	0.094		0.205
0.40FF50-II	0.003	0.023	0.021	0.039	0.124		0.222
0.50FF25-V	0.003	0.017	0.026	0.034	0.116		0.216
0.50CF25-V	0.003	0.017	0.018	0.032	0.105		0.188
0.50SL40-V	0.004	0.019	0.022	0.033	0.095		0.187
0.40FF25-V	0.003	0.017	0.020	0.037	0.123		0.208
0.40CF25-V	0.002	0.016	0.017	0.037	0.111		0.196
0.40SL40-V	0.003	0.016	0.016	0.033	0.110		0.198
0.40SF6-V	0.003	0.016	0.016	0.030	0.111		0.205
0.40FF50-V	0.003	0.021	0.020	0.038	0.137		0.200
0.50PC-II	0.003	0.018	0.019	0.034	0.102		0.170
0.40PC-II	0.002	0.018	0.023	0.037	0.127		0.198
0.50PC-V	0.002	0.012	0.013	0.031	0.092		0.171
0.40PC-V	0.002	0.015	0.018	0.029	0.107		0.195
0.50PC-II-IL	0.010	0.023	0.040	0.037	0.108		0.206
0.50PC-V-IL	0.006	0.020	0.030	0.038	0.105		0.191

Table 10 ASTM C1218 - Measured Water-Soluble Chloride Content, % cementitous

Mixture Designation	Measured Water-Soluble Chloride, % cementitious						
	Background	0.15% Level		0.30% Level	1.0% Level		2.0% Level
		TCG	NRMCA		TCG	NRMCA	
0.50FF25-II	0.025	0.140	0.142	0.286	0.689	0.739	1.276
0.50CF25-II	0.024	0.116	0.197	0.225	0.648		1.292
0.50SL40-II	0.030	0.127	0.187	0.250	0.710		1.239
0.40FF25-II	0.017	0.119	0.131	0.235	0.764	0.784	1.460
0.40CF25-II	0.026	0.128	0.129	0.234	0.737		1.417
0.40SL40-II	0.026	0.126	0.132	0.257	0.747		1.410
0.40SF6-II	0.019	0.108	0.113	0.243	0.633		1.378
0.40FF50-II	0.020	0.148	0.135	0.259	0.817		1.464
0.50FF25-V	0.025	0.125	0.196	0.256	0.865		1.616
0.50CF25-V	0.020	0.131	0.135	0.239	0.786		1.412
0.50SL40-V	0.026	0.139	0.163	0.250	0.716		1.406
0.40FF25-V	0.017	0.114	0.135	0.245	0.817		1.386
0.40CF25-V	0.015	0.106	0.115	0.248	0.740		1.314
0.40SL40-V	0.018	0.105	0.107	0.220	0.736		1.328
0.40SF6-V	0.020	0.108	0.105	0.198	0.747		1.375
0.40FF50-V	0.022	0.136	0.133	0.248	0.902		1.320
0.50PC-II	0.020	0.133	0.145	0.253	0.768		1.280
0.40PC-II	0.016	0.124	0.157	0.251	0.852		1.333
0.50PC-V	0.018	0.092	0.097	0.233	0.698		1.294
0.40PC-V	0.014	0.098	0.122	0.192	0.723		1.315
0.50PC-II-IL	0.075	0.170	0.295	0.269	0.789		1.507
0.50PC-V-IL	0.047	0.144	0.222	0.275	0.769		1.394

Table 11 Ratio of Measured Water-Soluble to Calculated Total Chloride Content

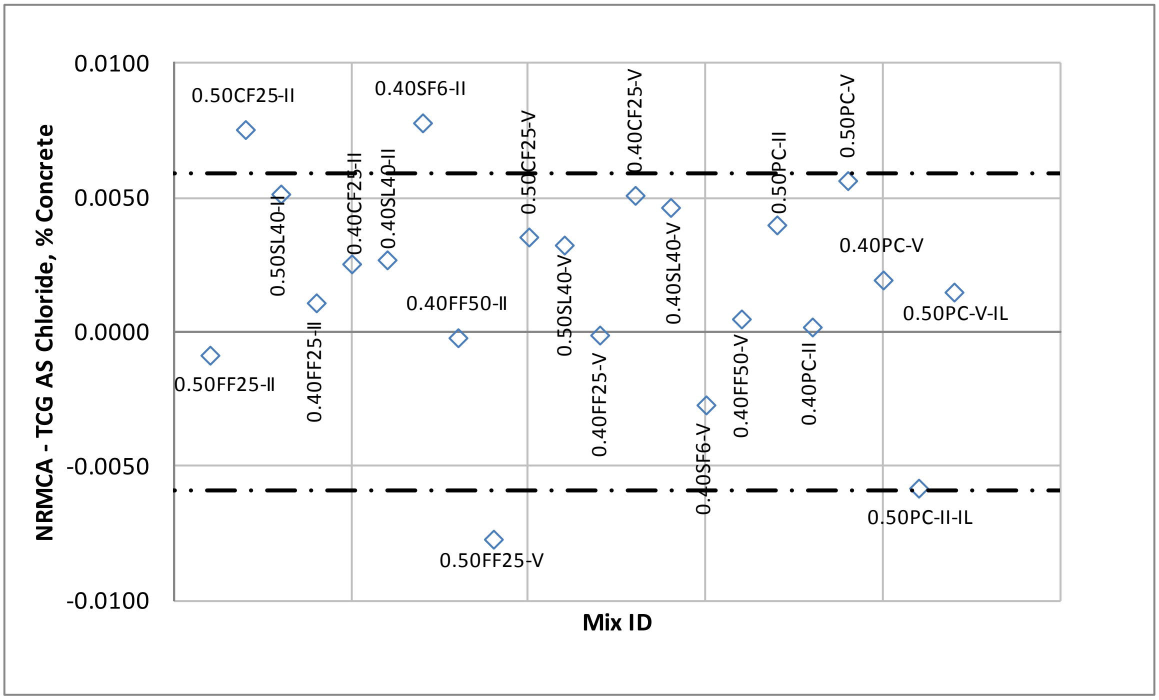
Mixture Designation	Measured Water-Soluble to Calculated Total Chloride						
	Background	0.15% Level		0.30% Level	1.0% Level		2.0% Level
		TCG	NRMCA		TCG	NRMCA	
0.50FF25-II	0.46	0.66	0.67	0.77	0.63	0.67	0.60
0.50CF25-II	0.42	0.54	0.92	0.61	0.59		0.60
0.50SL40-II	0.47	0.57	0.85	0.66	0.64		0.58
0.40FF25-II	0.34	0.58	0.64	0.65	0.70	0.72	0.68
0.40CF25-II	0.52	0.61	0.62	0.64	0.67		0.66
0.40SL40-II	0.45	0.59	0.61	0.69	0.68		0.66
0.40SF6-II	0.34	0.51	0.53	0.66	0.58		0.64
0.40FF50-II	0.41	0.72	0.66	0.72	0.75		0.69
0.50FF25-V	0.47	0.60	0.94	0.70	0.79		0.75
0.50CF25-V	0.38	0.62	0.64	0.65	0.72		0.66
0.50SL40-V	0.43	0.64	0.75	0.67	0.65		0.65
0.40FF25-V	0.36	0.56	0.66	0.68	0.75		0.65
0.40CF25-V	0.32	0.52	0.56	0.69	0.68		0.61
0.40SL40-V	0.33	0.50	0.50	0.60	0.67		0.62
0.40SF6-V	0.38	0.52	0.50	0.54	0.68		0.64
0.40FF50-V	0.48	0.67	0.66	0.69	0.83		0.62
0.50PC-II	0.35	0.62	0.68	0.68	0.70		0.60
0.40PC-II	0.31	0.59	0.75	0.69	0.78		0.62
0.50PC-V	0.33	0.44	0.46	0.63	0.64		0.60
0.40PC-V	0.28	0.48	0.60	0.53	0.66		0.62
0.50PC-II-IL	0.34	0.45	0.78	0.50	0.62		0.65
0.50PC-V-IL	0.21	0.38	0.59	0.52	0.61		0.60
Average	0.38	0.56	0.66	0.64	0.68		0.64

Table 12 Ratio of Measured Water-Soluble to Measured Acid-Soluble

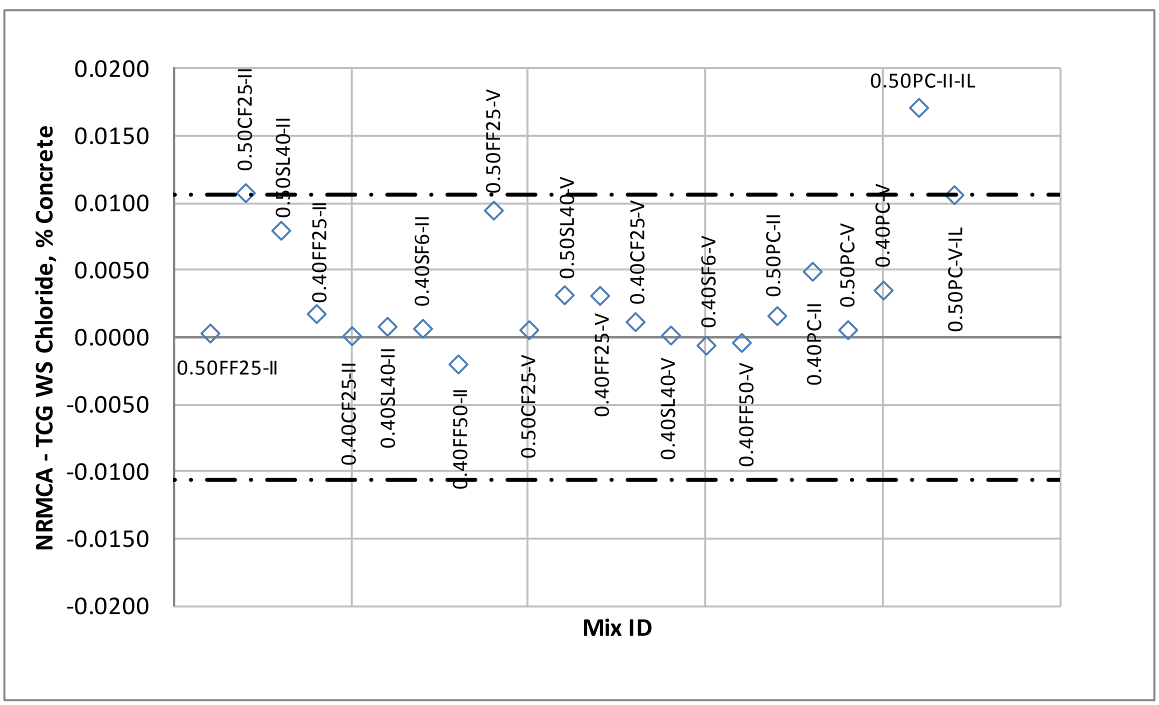
Mixture Designation	Measured Water-Soluble to Measured Acid-Chloride Chloride					
	Background	0.15% Level		1.0% Level		2.0% Level
		TCG	NRMCA	TCG	NRMCA	
0.50FF25-II	0.39	0.55	0.57	0.75	0.77	0.77
0.50CF25-II		0.58	0.77	0.65		0.70
0.50SL40-II		0.56	0.71	0.70		0.67
0.40FF25-II		0.58	0.61	0.71	0.77	0.77
0.40CF25-II		0.56	0.52	0.67		0.77
0.40SL40-II		0.57	0.55	0.69		0.72
0.40SF6-II		0.53	0.44	0.70		0.73
0.40FF50-II		0.63	0.58	0.80		0.85
0.50FF25-V	0.31	0.34	0.63	0.79		0.81
0.50CF25-V		0.54	0.51	0.73		0.77
0.50SL40-V		0.56	0.60	0.73		0.73
0.40FF25-V		0.52	0.61	0.76		0.77
0.40CF25-V		0.51	0.48	0.72		0.74
0.40SL40-V		0.51	0.45	0.71		0.72
0.40SF6-V		0.47	0.49	0.71		0.72
0.40FF50-V		0.63	0.61	0.78		0.82
0.50PC-II		0.63	0.60	0.80		0.82
0.40PC-II		0.54	0.69	0.77		0.71
0.50PC-V		0.49	0.42	0.74		0.74
0.40PC-V		0.45	0.53	0.69		0.75
0.50PC-II-IL	0.20	0.34	0.65	0.60		0.68
0.50PC-V-IL	0.21	0.33	0.49	0.62		0.69
Average	0.28	0.52	0.57	0.72		0.75

Table 13 Measured 1 Year Chloride and Changes from Early-Age Measurements

Mixture Designation	Water-Soluble Chloride			Change			Acid-Soluble	Change
	0.15% Level	0.30% Level	1.0% Level	0.15% Level	0.30% Level	1.0% Level	1.0% Level	1.0% Level
0.50FF25-II		0.0351			-8%			
0.50CF25-II		0.0361			21%			
0.50SL40-II		0.0305			-8%			
0.40FF25-II	0.0155	0.0299	0.0928	-13%	-15%	-19%	0.1472	-8%
0.40CF25-II	0.0185	0.0385	0.1113	-3%	10%	1%		
0.40SL40-II	0.0192	0.0355	0.117	2%	-7%	5%		
0.40SF6-II		0.0298			-18%			
0.40FF50-II		0.042			7%			
0.50FF25-V		0.0167			-51%			
0.50CF25-V		0.0323			1%			
0.50SL40-V		0.032			-4%			
0.40FF25-V		0.0351			-4%			
0.40CF25-V		0.0324			-13%			
0.40SL40-V	0.0164	0.0334	0.1122	4%	2%	2%		
0.40SF6-V		0.0303			3%			
0.40FF50-V		0.0368			-2%			
0.50PC-II		0.0313			-7%			
0.40PC-II	0.0148	0.031	0.096	-19%	-17%	-24%	0.1459	-11%
0.50PC-V		0.0301			-2%			
0.40PC-V	0.012	0.0274	0.1091	-18%	-4%	2%		
0.50PC-II-IL		0.033			-10%			
0.50PC-V-IL		0.036			-4%			
Average				-8%	-6%	-6%		-10%



(a)



(b)

Figure 1 TCG VS NRMCA for the 0.15% chloride level a) acid-soluble data b) water soluble data

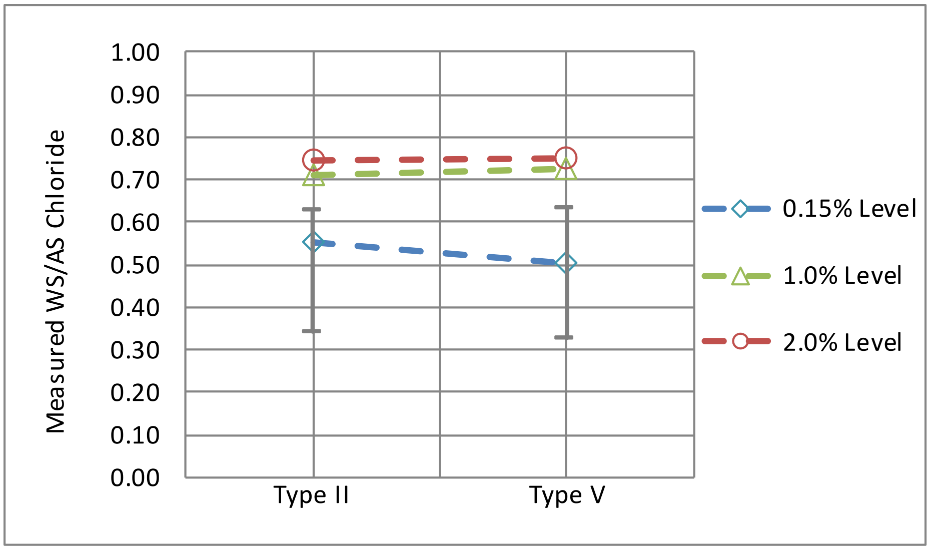


Figure 2 Measured water-soluble: acid-soluble (TCG) for mixtures with Type II vs. Type V cement (average of 11 mixtures for each cement type)

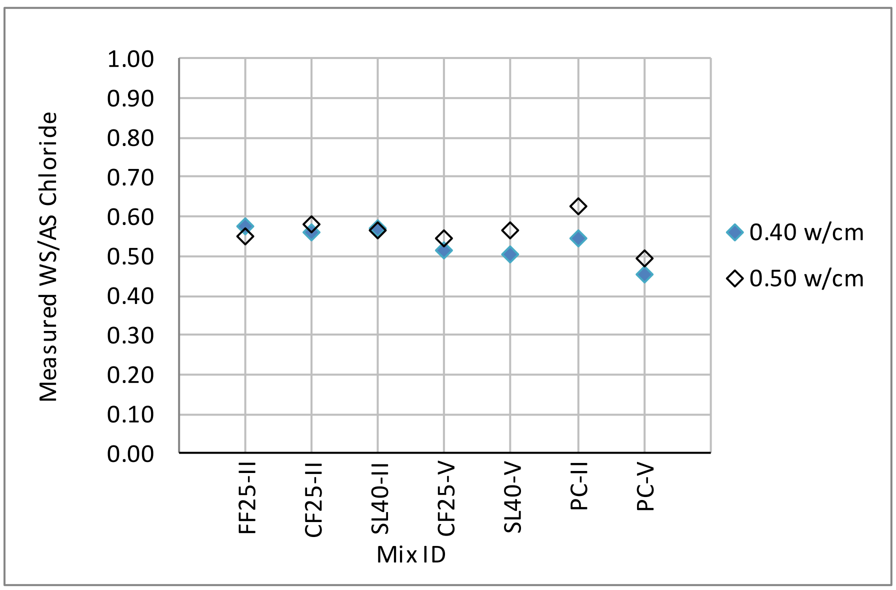
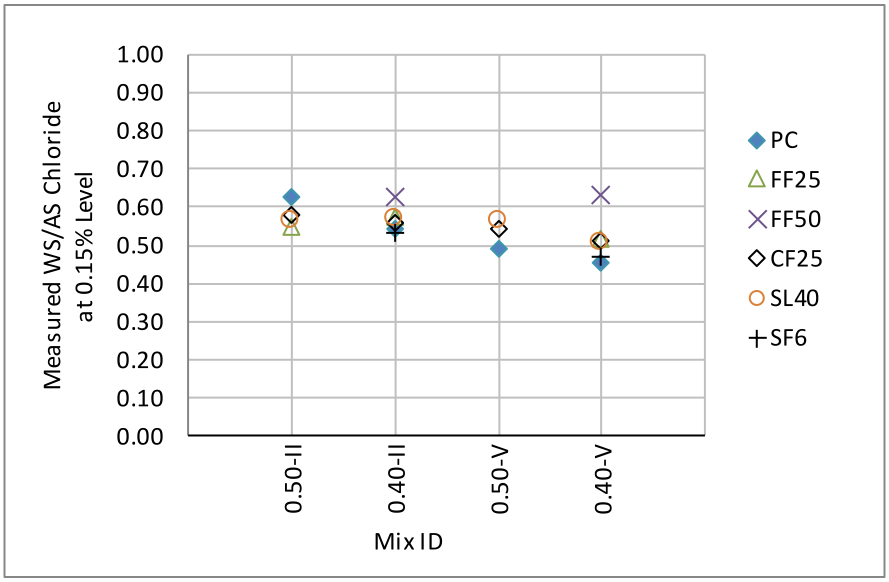
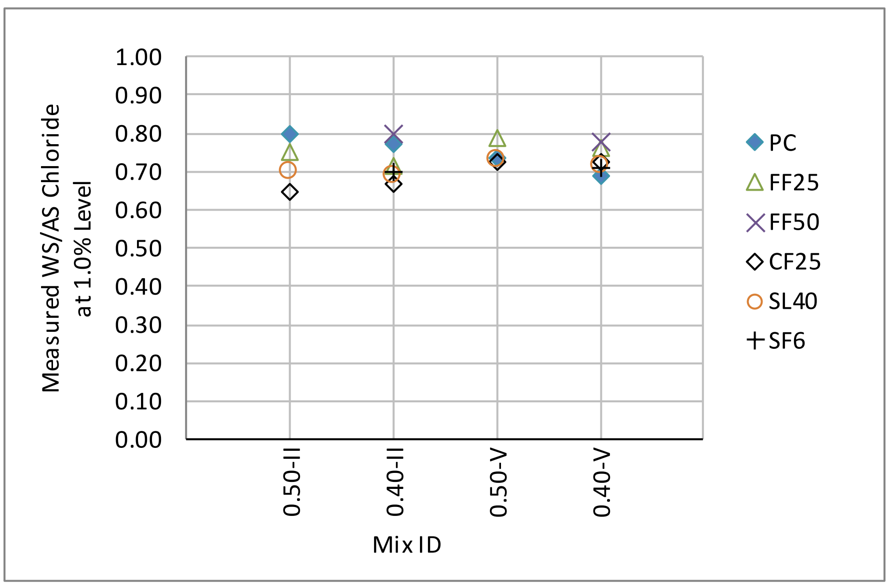


Figure 3 Measured water-soluble: acid-soluble (TCG) for the 0.50 mixtures vs 0.40 mixtures at 0.15% chloride level



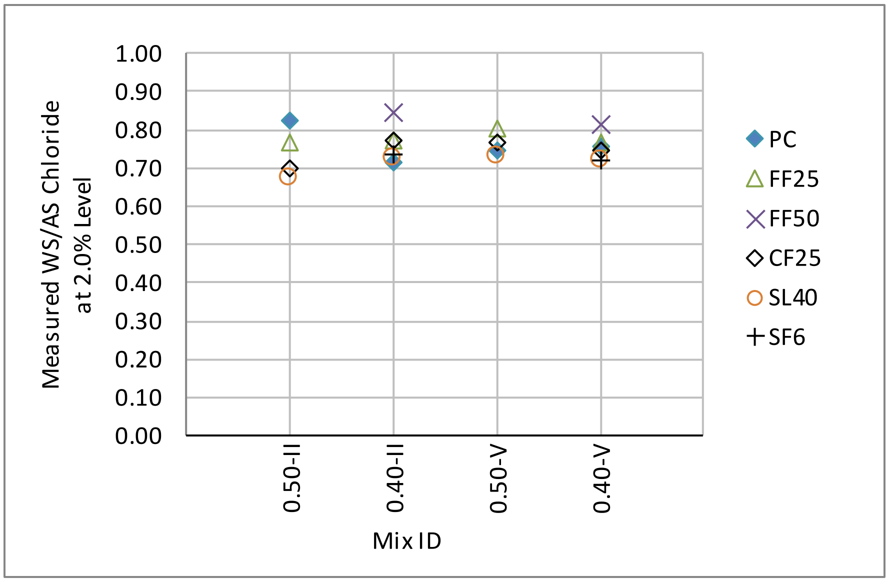
Measured WS/AS Chloride at 0.15% Level
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0.50-II
0.40-II
0.50-V
0.40-V
Mix ID
PC
FF25
FF50
CF25
SL40
SF6

(a)



Measured WS/AS Chloride at 1.0% Level
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0.50-II
0.40-II
0.50-V
0.40-V
Mix ID
PC
FF25
FF50
CF25
SL40
SF6

(b)



(c)

Figure 4 Measured water-soluble: acid-soluble (TCG) for the SCM vs PC mixtures (a) at 0.15% Level (b) at 1.0% Level (c) at 2.0% Level

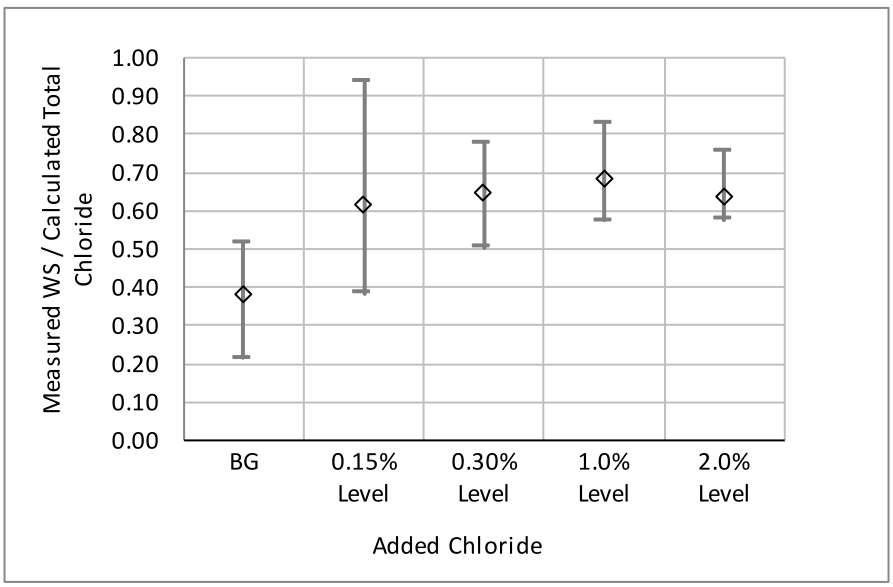


Figure 5 (TCG and NRMCA Measured water-soluble): Calculated Total Chlorides for all Mixtures