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Effect of Shrinkage-Reducing Admixtures on Chloride-Ion Penetrability of Concrete

By Tarun R. Naik[1]; Rudolph N. Kraus[2]; Yoon-moon Chun[3]; and Fethullah Canpolat[3]

Abstract: This research reports on evaluation of the effects of shrinkage-reducing admixtures (SRAs) on chloride ion penetrability of concrete.

Shrinkage-reducing admixtures (SRAs) from three manufacturers (SRA-1, Eucon SRA from Euclid; SRA-2, Eclipse Plus from Grace; and SRA-3, Tetraguard AS20 from Degussa) were evaluated in WisDOT Grade A no-ash, Grade A-FA Class C fly ash, and selected high-cementitious concrete mixtures. In most cases, SRA-1 and SRA-3 also worked similar to like water-reducing admixtures and often increased the strength and the resistance to chloride-ion penetration. SRA-2 sometimes decreased the strength and did not considerably affect the chloride-ion penetrability. All three SRAs did not noticeably affect the changes in air content and slump of fresh concrete mixtures during the first hour.

Effects of SRAs on aggregate type, and chloride-ion penetration into the concrete are reported.

CE Data base subject headings: Admixtures; Aggregate; Concrete; Shrinkage; Strength.

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Introduction

Concrete is one of the most durable construction materials. However, cracking adversely affects its durability, functionality, and appearance. Cracked concrete typically needs to be repaired to prevent further deterioration due to freezing and thawing, ingress of chemicals including water, and corrosion of steel reinforcement resulting from infiltration of water with or without chloride ions from de-icing salts. Cracking leads to additional costs for repairs to prevent premature deterioration of the concrete. Cracking can significantly reduce the service life of concrete bridge decks, pavements, and other concrete structures.

Shrinkage cracking is a major cause of concern for concrete structures. In addition to potentially weakening the structure, these shrinkage cracks have the potential to allow infiltration of moisture and chloride ions that accelerate the corrosion of steel reinforcement and reduce the durability of concrete (Gilbert, 2001). The four main types of shrinkage associated with concrete are plastic shrinkage, autogenous shrinkage, carbonation shrinkage, and drying shrinkage.

Shrinkage-reducing admixtures (SRAs) have been used recently to reduce the autogenous shrinkage and drying shrinkage of concrete. References on shrinkage-reducing admixtures in technical literature trace their origin to Japan during in the 1980s. SRA composition varies depending on the manufacturer, but it generally consists of a surface-active organic polymer solution. SRAs are designed with the specific aim of reducing the surface tension of the pore solution. As a result, SRA reduces capillary stresses within the pore structure that are responsible for the shrinkage in concrete that is subjected to air-drying or internal self-desiccation (Roncero, 2003).

Ribeiro et. al (Ribeiro et. al, 2003) have reported effectiveness of shrinkage-reducing admixtures on different concrete mixtures using two SRA products at different dosage rates. All the mixtures were prepared with 25% replacement of cement by fly ash. Their study showed a maximum reduction in drying shrinkage of about 30% with the use of SRA. They attributed the reduction in shrinkage to the reduction of capillary tension in concrete pores with the use of SRAs. The reduction in shrinkage was related to admixture dosage. The maximum reduction in drying shrinkage was obtained with the maximum dosage of SRA. It was also observed that there was a reduction in compressive strength due to incorporation of SRAs. The reduction in compressive strength was more pronounced at early ages.

Use of shrinkage-reducing admixtures is advocated as one of the ways of reducing shrinkage cracking. The reduction in capillary tension by organic agents of shrinkage-reducing admixtures decreases the concrete volume changes due to internal self-desiccation or air drying of concrete (Ribeiro 2003). “The molecules of the shrinkage-reducing admixture reduce capillary tension in concrete pores; however, these molecules may be absorbed during the hydration of cementitious materials thereby reducing the effectiveness of the shrinkage-reducing admixture over time.” In one case, it was reported that the use of shrinkage-reducing admixtures could increase setting time and reduce compressive strength of concrete, and affect air-void system in concrete (Bentz, 2002).

Roncero et. al (Roncero et. al, 2003) evaluated the influence of SRA on the microstructure and long-term behavior of concrete. In their study, concrete mixtures were prepared at 0.4 W/C and with 0% (reference), 1%, and 2% of SRA by mass of cement. After two years of drying at 50% relative humidity, the drying shrinkage strain reduced by about 26% and 51% for the concrete mixtures with 1% and 2% of SRA, respectively, compared to the reference mixture. On the other hand, in sealed condition, a slight expansion was observed for both the 1% and 2% SRA concrete mixtures. The reference concrete mixture showed autogenous shrinkage, especially during the first three weeks. A reduction in compressive strength was also observed with incorporation of SRA.

Berke et. al (Berke et. al, 2003) have studied the performance of concrete containing a brand of glycol-ether based SRA. The aim of the study was to produce concrete with good quality air-void systems needed for freezing and thawing resistance, while reducing shrinkage with the SRA. The results showed that good air-void systems were obtainable with that particular glycol-ether based SRA. However, this was not always the case, especially when the air-entraining admixture (AEA) and mixture proportions were not properly selected to maintain the quality of the air-void system when using the SRA.

Experimental Program

Materials

Type I portland cement (ASTM C 150) was used in this work. ASTM Class C fly ash was obtained from the We Energies' Pleasant Prairie Power Plant (P4), which met the requirements of ASTM Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete (C 618). Natural sand was used as fine aggregate. The sand met the requirements of ASTM C 33. Three types of coarse aggregate were used in this research: A1, crushed quartzite stone; A2, semi-crushed river gravel; and A3, crushed dolomitic limestone. The coarse aggregates met the requirements of ASTM C 33. All of the three types of coarse aggregate had a maximum size of 3/4 inches and met the grading requirements for WisDOT Size No. 1 (AASHTO No. 67). Shrinkage-reducing admixtures (SRAs) were supplied by three manufacturers (SRA-1, Eucon SRA from Euclid; SRA-2, Eclipse Plus from Grace; and SRA-3, Tetraguard AS20 from Degussa).

Mixtures

Table 1, 2 and 3 show the mixture proportions and fresh properties of WisDOT Grade A, Grade A-FA, and CBU high-Cm A-FA-A concrete mixtures made with chemical admixture from Source 1 (Euclid), Source 2 (Eclipse Plus) and Source 3 (Tetraguard AS20) and coarse aggregate A1 (crushed quartzite stone). The table also includes Grade A-FA mixtures made with coarse aggregates A2 (semi-crushed river gravel) and A3 (crushed dolomitic limestone).

SRA was used with mid-range water-reducing admixture (MRWRA) and air-entraining admixture (AEA) supplied by the same manufacturer. In this research, SRA was added last into a concrete mixer after all the other ingredients were intermixed.

Various concrete mixtures were produced based on WisDOT Grade A no-ash concrete, Grade A-FA Class C fly ash concrete, and selected high-cementitious concrete mixture proportions. For all concrete mixtures, the coarse aggregate used had a maximum size of 3/4 inches. Except for Grade A mixtures, Class C fly ash was used as a partial replacement of 35% of cement. The high-cementitious concrete used 30% more cement and fly ash than Grade A-FA concrete.

The produced concrete mixtures were tested for air content, slump, initial setting time, and chloride-ion penetrability. Some mixtures were also tested to evaluate the effect of SRAs on the changes in the air content and slump of fresh concrete mixtures during the first hour.

Effects of three types of coarse aggregate were also evaluated using Grade A-FA mixture proportions: Aggregate 1, crushed quartzite stone; Aggregate 2, semi-crushed river gravel; and Aggregate 3, crushed dolomitic limestone.

Specimen preparation and testing

Test specimens were made and cured according to the ASTM Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory (C 192).

The concrete mixer used in this research was electrical power-driven, revolving drum, tilting mixer.

Test specimens were prepared for time of initial setting (ASTM C 403), and Electrical indication of chloride-ion penetrability (ASTM C 1202).

The properties of freshly mixed concrete were determined, and test specimens were cast for the evaluation of time of initial setting, and chloride-ion penetrability of concrete.

The specimens for time of setting were kept in sealed condition. To prevent evaporation of water from the unhardened concrete specimens for strength and chloride-ion penetrability, the cast specimens were covered with either lids or plastic sheets. The specimens were removed from the molds 24 ± 8 hours after casting. The demolded specimens were moist cured at 23 ± 2 °C, in a moist room at a relative humidity of not less than 95% or in lime-saturated water.

Results and Discussion

Table 1 shows the mixture proportions and fresh properties of WisDOT Grade A, Grade A-FA, and CBU high-Cm A-FA-A concrete mixtures made with chemical admixture from Source 1 (Euclid) and coarse aggregate A1 (crushed quartizite stone). The table also includes Grade A-FA mixtures made with coarse aggregates A2 (semi-crushed river gravel) and A3 (crushed dolomitic limestone).

Table 2 shows the mixture proportions and fresh properties of concrete mixtures containing chemical admixtures from Source 2 (Grace).

Table 3 shows the mixture proportions and fresh properties of concrete mixtures containing chemical admixtures from Source 3 (Degussa, formerly Master Builders).

Compressive Strength (Chemical 1)

The test results for compressive strength of concrete are shown in Table 4.

The concrete mixtures containing SRA-1 generally showed somewhat higher compressive strength than their reference (no SRA) concrete mixtures. The SRA-1 concrete mixtures usually had a lower W/Cm compared with the reference concrete mixtures (Table 1). SRA-1 itself does not seem to have affected the compressive strength of concrete considerably. At 1 day only, some SRA-1 concrete mixtures (S1-24, S1-24-FA, S1-24-FA-H) showed a little lower compressive strength than their reference concrete mixtures (Table 4). The remaining SRA-1 concrete mixtures showed higher compressive strength than their reference concrete mixtures at all test ages. SRA-1 improved the workability of concrete mixtures; therefore, the use of SRA-1 reduced the MRWRA-1 demand and sometimes even the W/Cm of the mixtures, resulting in higher compressive strength of concrete.

Compressive Strength (Chemical 2)

The test results for compressive strength of concrete are shown in Table 5.

The concrete mixtures containing SRA-2 showed generally lower compressive strength than their reference (no SRA) concrete mixtures. SRA-2 lowered the compressive strength of concrete when used in Grade A no-ash concrete mixtures (S2-00-A1, S2-1.8-A1, and S2-3.0-A1), the high-Cm mixtures (S2-00-FA-H-A1, S2-2.0-FA-H-A1), and Grade A-FA fly ash concrete mixtures made with Aggregates 2 and 3 (S2-00-FA-A2, S2-1.8-FA-A2, S2-00-FA-A3, and S2-1.8-FA-A3). As the only exception, SRA-2 either did not noticeably affect or slightly increased the compressive strength when used in Grade A-FA fly ash concrete mixtures made with Aggregate 1 (S2-1.8-FA-A1, S2-3.0-FA-A1, and S2-3.0-FA-A1). The generally lower compressive strength of the concrete mixtures containing SRA-2 is possibly due to the use of very high dosages of AEA-2. The W/Cm and density of concrete mixtures alone do not give a satisfactory answer as to the cause of the reduction in compressive strength. Compared with the reference (no SRA) concrete mixtures, the concrete mixtures containing SRA-2 generally had a higher W/Cm, a lower air content, and a higher density.

Compared with Grade A no-ash concrete mixtures (S2-00-A1, S2-1.8-A1, and S2-3.0-A1), Grade A-FA fly ash concrete mixtures (S2-00-A1, S2-1.8-A1, and S2-3.0-A1) showed a lower compressive strength at early ages, and a higher compressive strength at later ages (Table 5).

The high-Cm concrete mixtures showed a higher compressive strength than corresponding Grade A-FA fly ash concrete mixtures (S2-00-A1, S2-1.8-A1, and S2-3.0-A1). Compared with corresponding Grade A no-ash concrete mixtures, the high-Cm concrete mixtures showed a higher compressive strength at all test ages, except at 1 day (Table 5).

The concrete mixtures made with Aggregates 1 and 3 (both crushed stone) generally showed a higher compressive strength than the concrete mixtures made with Aggregate 2 (semi-crushed river gravel). The mixtures made with Aggregate 3 showed the highest compressive strength, and the mixtures made with Aggregate 1 showed the second highest compressive strength (Table 5).

Compressive Strength (Chemical 3)

The test results for compressive strength of concrete are shown in Table 6.

SRA-3 did not affect the compressive strength of Grade A no-ash concrete mixtures (S3-00-A1, S3-1.8-A1, and S3-2.5-A1). The Grade A-FA fly ash concrete mixtures containing SRA-3, due to their relatively low W/Cm, showed somewhat higher compressive strength than the reference (no SRA) Grade A-FA fly ash concrete mixture (S3-00-FA-A1, S3-1.8-FA-A1, and S3-2.5-FA-A1). SRA-3 itself does not seem to have affected the compressive strength of concrete considerably.

Compared with Grade A no-ash concrete mixtures, Grade A-FA fly ash concrete mixtures showed a lower compressive strength at ages of up to 14 days, and a similar compressive strength at 28 days and beyond (Table 6).

The reference (no SRA) high-Cm concrete mixture (S3-00-FA-H-A1) showed a slightly higher compressive strength than the reference (no SRA) Grade A-FA fly ash concrete mixture (S3-00-FA-A1). When SRA-3 was used in the high-Cm concrete, the compressive strength increased significantly due to a reduction in W/Cm. Compared with the reference (no SRA) Grade A no-ash concrete, the reference (no SRA) high-Cm concrete generally showed a lower compressive strength especially at early ages (Table 6). Compared with the Grade A no-ash concrete S3-27, the high-Cm concrete S3-27-FA-H showed a higher compressive strength at 3 days and later (Table 6).

The concrete mixtures made with Aggregates 1 and 3 (both crushed stone) showed generally higher compressive strength than the concrete mixtures made with Aggregate 2 (semi-crushed river gravel).

The mixtures made with Aggregate 3 showed the highest compressive strength, followed by those made with Aggregate 1 (Table 6).

Chloride-Ion Penetrability (Chemical 1)

The test results for electrical indication of chloride-ion penetrability into concrete are shown in Table 7, and through Fig. 1 through Fig. 10.

As the age increased, the chloride-ion penetrability decreased due to improvement in microstructure of cementitious paste in concrete. Use of SRA-1 was somewhat helpful in reducing the chloride-ion penetrability into Grade A no-ash concrete (a higher resistance to penetration) (Fig. 1, Fig. 2). Grade A-FA fly ash concrete mixtures showed much higher resistance to chloride-ion penetration (a lower penetrability into concrete) than their Grade A no-ash counterparts (Fig. 5, Fig. 6). Use of more cementitious materials did not noticeably improve the resistance of concrete to chloride-ion penetration (Fig. 7, Fig. 8). Use of SRA-1 in high-Cm concrete mixtures did not noticeably affect their resistance to chloride-ion penetration.

As for the effect of the type of aggregate, Aggregate 1 was the best, leading to the lowest penetrability (the highest resistance to penetration) (Fig. 9, Fig. 10). Aggregate 2 was the second best, and the concrete mixtures made with Aggregate 3 allowed the highest penetrability of chloride ions into concrete (the lowest resistance to penetration). The compressive strength of concrete mixtures containing Aggregate 2 was lower than that of the concrete mixtures made with Aggregate 1 or 3 (Table 4). So, there was no correlation between the compressive strength and the chloride-ion penetration resistance of concrete in this case. Use of SRA-1 itself did not significantly increase or decrease the chloride-ion penetrability into Grade A-FA fly ash concrete (Fig. 9).

Chloride-Ion Penetrability (Chemical 2)

The test results for electrical indication of chloride-ion penetrability into concrete are shown in Table 8, and through Fig. 11 through Fig. 20.

As the age increased, the chloride-ion penetrability decreased due to improvement in microstructure of cementitious paste in concrete.

Use of SRA-2 was helpful in reducing the 28-day chloride-ion penetrability into Grade A no-ash concrete (Fig. 11, Fig. 12) and Grade A-FA fly ash concrete mixtures made with Aggregates 1 and 2 (Fig. 13, Fig. 14, Fig. 19, Fig. 20). On the other hand, SRA-2 somewhat increased the chloride-ion penetrability into the high-Cm concrete and Grade A-FA fly ash concrete made with Aggregate 3 (a lower resistance to penetration).

The chloride-ion penetrability into Grade A-FA fly ash concrete mixtures was much lower (higher resistance to penetration) than that into Grade A no-ash concrete mixtures (Fig. 15, Fig. 16). Overall, the use of higher amounts of cementitious materials did not significantly affect the chloride-ion penetrability into concrete (Fig. 17, Fig. 18).

When used without SRA-2, use of Aggregate 3 led to the lowest 28-day chloride-ion penetrability (the highest resistance to penetration) (Fig. 20); the 56-day and 182-day chloride-ion penetrability was similar regardless of aggregate type. When used with SRA-2, Aggregate 1 led to the lowest early-age chloride-ion penetrability (the highest resistance to penetration), followed by Aggregate 2, and Aggregate 3.

Chloride-Ion Penetrability (Chemical 3)

The test results for electrical indication of chloride-ion penetrability into concrete are shown in Table 9, and through Fig. 21 through Fig. 30.

As the age increased, the chloride-ion penetrability decreased due to improvement in microstructure of cementitious paste in concrete.

Use of SRA-3 reduced the chloride-ion penetrability into concrete (a higher resistance to penetration) for all of the concrete mixtures at all ages, except in the case of the Grade A-FA fly ash concrete mixtures made with Aggregate 2 for which SRA-3 did not affect the chloride-ion penetrability noticeably (Table 9).

The chloride-ion penetrability into Grade A-FA fly ash concrete mixtures was lower (a higher resistance to penetration) compared with corresponding Grade A no-ash concrete mixtures at 56 and 182 days (Fig. 25, Fig. 26). Use of higher amounts of cementitious materials decreased the chloride-ion penetrability into concrete (Fig. 27, Fig. 28).

When used without SRA-3, use of Aggregate 2 led to the lowest chloride-ion penetrability (the highest resistance to penetration) at 28 and 56 days (Fig. 29, Fig. 30); the 182-day chloride-ion penetrability was similar regardless of the type of coarse aggregate. When used with SRA-3, the chloride-ion penetrability was not noticeably influenced by the aggregate type.

Conclusions

The main objective of this research was to evaluate the effectiveness of three different brands of shrinkage-reducing admixtures (SRA-1, SRA-2, and SRA-3) on chloride-ion penetrability.

Many times, SRA-1 and SRA-3 worked like water-reducing admixtures and significantly reduced the required amounts of MRWRAs. SRA-2 generally did not have a considerable water-reducing effect.

Each SRA had a different effect on the AEA demand. SRA-1 reduced the AEA-1 demand significantly, bringing it close to zero. When SRA-2 was used with AEA-2 and MRWRA-2, the AEA-2 demand increased sharply and the air content and strength of concrete generally decreased. When SRA-3 was used at its maximum dosage, it increased the AEA-3 demand.

Fresh concrete mixtures had an initial air content of 6 ± 1.5%. SRAs did not significantly affect the changes in air content and slump of fresh concrete mixtures during the first hour after the concrete was mixed. The changes in air content and slump during the first hour were about the same regardless of whether SRAs were used or not. Thus, there was no adverse effect of the SRAs on the initial air content, air-content stability, and slump retention of fresh concrete.

Usually, SRA-1 and SRA-3 either did not affect or increased the compressive strength. Concrete mixtures made with chemical admixtures from Source 2 showed a relatively low compressive strength. An increase in SRA-2 dosage either did not affect or lowered the compressive strength. This could be due to the significant increase in AEA-2 demand with increasing SRA-2 dosage.

SRA-1 and SRA-3 either did not affect or improved the resistance of concrete to chloride-ion penetration (less chloride-ion penetration into concrete).

SRA-2 did not considerably affect the chloride-ion penetrability.

Concrete mixtures containing chemical admixtures from Source 1 showed the highest resistance to chloride-ion penetration (the least penetration). The concrete mixtures containing chemical admixtures from Source 2 generally showed the lowest resistance to chloride-ion penetration at 182 days (the highest penetration), most likely due to the relatively lower strength of these concrete mixtures

Use of Aggregate 3 led to the highest compressive strength of concrete, followed by Aggregate 1, and Aggregate 2 (the lowest compressive strength).

The type of coarse aggregate did not noticeably affect the 182-day chloride-ion penetrability into concrete.

Compared to Grade A-FA fly ash concrete, the high-cementitious concrete with a higher cementitious materials content (leading to lower W/Cm) generally exhibited higher compressive strength and higher resistance to chloride-ion penetration.

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Table 1. Mixture Proportions and Fresh Properties of Concrete (SRA-1)

Mixture designation*	S1-00-A1	S1-1.6-A1	S1-2.1-A1	S1-00-FA-A1	S1-1.6-FA-A1	S1-2.1-FA-A1	S1-00-FA-H-A1	S1-1.6-FA-H-A1	S1-00-FA-A2	S1-1.6-FA-A2	S1-00-FA-A3	S1-1.6-FA-A3
Cement (kg/m^3)	321	327	327	234	233	228	302	305	229	234	236	238
Class C Fly Ash (kg/m^3)	0	0	0	101	100	98	130	131	99	101	102	103
Water (kg/m^3)	140	128	128	134	125	132	141	133	131	121	136	140
W/Cm	0.44	0.39	0.39	0.40	0.37	0.41	0.33	0.30	0.40	0.36	0.40	0.41
Fine aggregate, SSD (kg/m^3)	809	822	824	832	829	810	778	784	725	740	840	849
Coarse aggregate, max 19-mm, SSD (kg/m^3)	981	997	999	1010	1000	982	941	951	1090	1110	1030	1040
MRWRA-1 (L/m^3)	2.74	0.83	0.83	0.85	0.84	0.83	1.13	1.13	0.49	0.20	1.23	0.48
AEA-1 (L/m^3)	0.12	0.03	0.02	0.15	0.02	0.06	0.23	0.05	0.16	0.02	0.86	3.77
SRA-1 (L/m^3))	0.00	5.16	6.90	0.00	5.26	6.87	0.00	6.85	0.00	5.29	0.00	6.29
Slump (mm.)	57	51	51	51	51	38	51	51	76	89	70	57
Air content (%)	7.2	7.5	6.7	6.0	6.4	7.5	5.7	6.0	6.0	6.4	6.4	4.8
Air temperature (°C)	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.0	21.1	20.3	20.0	20.0
Concrete temperature (°C)	21.1	21.1	21.1	21.1	21.1	21.1	21.1	21.1	20.6	21.4	19.4	20.0
Density (kg/m^3)	2250	2280	2290	2310	2300	2260	2290	2310	2270	2310	2340	2370

* The number following S1- indicates the approximate dosage rate of SRA-1 in L/100 kg of cementitious materials.

Table 2. Mixture Proportions and Fresh Properties of Concrete (SRA-2)

Mixture designation*	S2-00-A1	S2-1.8-A1	S2-3.0-A1	S2-00-FA-A1	S2-1.8-FA-A1	S2-3.0-FA-A1	S2-00-FA-H-A1	S2-2.0-FA-H-A1	S2-00-FA-A2	S2-1.8-FA-A2	S2-00-FA-A3	S2-1.8-FA-A3
Cement (kg/m^3)	323	328	326	227	230	234	300	297	232	234	236	238
Class C Fly Ash (kg/m^3)	0	0	0	98	99	101	129	128	100	101	102	103
Water (kg/m^3)	142	144	147	131	131	141	156	153	128	138	136	140
W/Cm	0.44	0.44	0.45	0.40	0.40	0.42	0.36	0.36	0.39	0.41	0.40	0.41
Fine aggregate, SSD (kg/m^3)	813	825	821	806	817	832	771	764	732	740	840	849
Coarse aggregate, max 19-mm, SSD (kg/m^3)	985	999	994	976	990	1010	934	926	1100	1110	1030	1040
MRWRA-1 (L/m^3)	1.91	1.93	2.60	0.78	0.64	0.63	0.81	0.81	0.49	0.50	1.23	0.48
AEA-1 (L/m^3)	0.23	4.26	6.86	0.86	4.26	6.86	1.59	5.57	0.77	3.24	0.86	3.77
SRA-1 (L/m^3))	0.00	5.95	9.62	0.00	5.97	9.89	0.00	8.42	0.00	6.19	0.00	6.29
Slump (mm.)	114	57	51	114	70	76	70	89	76	57	70	57
Air content (%)	6.5	5.4	4.6	7.4	5.9	4.6	5.7	4.8	7.0	4.6	6.4	4.8
Air temperature (°C)	20.6	20.0	20.6	20.0	20.6	20.6	20.6	20.6	19.3	21.1	20.0	20.0
Concrete temperature (°C)	21.1	21.1	21.1	20.6	21.1	21.1	21.1	21.1	21.1	21.7	19.4	20.0
Density (kg/m^3)	2260	2300	2300	2240	2270	2330	2290	2280	2290	2330	2340	2370

* The number following S2- indicates the approximate dosage rate of SRA-2 in L/100 kg of cementitious materials.

Table 3. Mixture Proportions and Fresh Properties of Concrete (SRA-3)

Mixture designation*	S3-00-A1	S3-1.8-A1	S3-2.5-A1	S3-00-FA-A1	S3-1.8-FA-A1	S3-2.5-FA-A1	S3-00-FA-H-A1	S3-1.8-FA-H-A1	S3-00-FA-A2	S3-1.8-FA-A2	S3-00-FA-A3	S3-1.8-FA-A3
Cement (kg/m^3)	326	330	326	233	230	229	296	303	233	233	240	238
Class C Fly Ash (kg/m^3)	0	0	0	100	99	99	127	130	100	101	103	102
Water (kg/m^3)	134	132	132	134	119	123	145	129	124	130	137	132
W/Cm	0.41	0.40	0.41	0.40	0.36	0.37	0.34	0.30	0.37	0.39	0.40	0.39
Fine aggregate, SSD (kg/m^3)	822	831	821	828	817	814	761	779	735	740	853	850
Coarse aggregate, max 19-mm, SSD (kg/m^3)	996	1010	995	1000	990	986	922	944	1100	1100	1040	1040
MRWRA-1 (L/m^3)	3.16	0.64	1.66	1.61	0.64	0.62	0.83	0.85	0.94	0.03	1.38	0.17
AEA-1 (L/m^3)	0.06	0.10	0.39	0.11	0.14	0.30	0.59	0.52	0.21	0.04	0.09	0.06
SRA-1 (L/m^3))	0.00	5.87	8.05	0.00	5.75	8.09	0.00	7.57	0.00	5.93	0.00	6.04
Slump (mm.)	76	64	51	83	70	70	76	57	70	95	57	57
Air content (%)	6.2	5.8	6.2	5.7	7.2	6.0	7.2	6.3	6.0	5.8	5.5	5.5
Air temperature (°C)	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.0	20.0	19.4	20.0
Concrete temperature (°C)	20.6	21.1	21.1	21.1	21.1	21.1	21.1	21.1	20.0	21.1	19.4	18.9
Density (kg/m^3)	2280	2306	2283	2299	2261	2259	2251	2293	2290	2310	2380	2370

* The number following S3- indicates the approximate dosage rate of SRA-3 in L/100 kg of cementitious materials.

Table 4. Compressive Strength of Concrete (Chemical 1)

Age (days)	Compressive strength (MPa)											
	S1-00-A1	S1-1.6-A1	S1-2.1-A1	S1-00-FA-A1	S1-1.6-FA-A1	S1-2.1-FA-A1	S1-00-FA-H-A1	S1-1.6-FA-H-A1	S1-00-FA-A2	S1-1.6-FA-A2	S1-00-FA-A3	S1-1.6-FA-A3
1	16.3	15.0	17.7	9.0	7.9	11.7	14.3	11.5	5.7	7.2	5.6	7.5
3	27.2	30.2	31.9	22.2	25.8	27.0	30.6	31.1	18.8	22.0	19.6	24.6
7	34.3	35.3	34.6	31.1	34.2	35.8	36.6	40.1	25.7	30.2	28.5	34.4
14	33.7	37.2	39.9	36.0	40.1	38.6	42.6	46.3	30.8	35.2	35.8	42.4
28	38.7	40.2	41.8	39.4	46.6	46.0	48.4	50.8	33.3	39.5	37.9	48.3
91	44.8	44.8	48.6	49.1	55.1	54.7	55.2	57.7	42.3	46.8	41.5	57.0
182	48.4	51.3	55.6	50.9	56.7	57.3	59.9	66.1	44.3	49.0	42.3	60.3

Table 5. Compressive Strength of Concrete (Chemical 2)

Age (days)	Compressive strength (MPa)											
	S2-00-A1	S2-1.8-A1	S2-3.0-A1	S2-00-FA-A1	S2-1.8-FA-A1	S2-3.0-FA-A1	S2-00-FA-H-A1	S2-2.0-FA-H-A1	S2-00-FA-A2	S2-1.8-FA-A2	S2-00-FA-A3	S2-1.8-FA-A3
1	12.6	8.7	5.9	5.0	5.2	3.7	9.9	5.9	4.6	4.6	5.4	3.7
3	20.6	15.4	15.7	13.5	17.0	14.4	22.1	17.4	14.9	12.5	20.6	18.1
7	26.3	17.9	20.0	20.8	22.4	19.3	27.8	22.8	21.7	21.4	29.4	26.6
14	28.1	21.7	22.5	22.8	25.8	24.1	31.0	24.7	24.8	23.5	34.8	31.2
28	29.7	25.5	24.9	31.2	31.8	27.9	38.1	34.6	29.6	25.9	42.8	36.6
91	38.5	29.4	28.4	38.0	41.3	37.7	49.7	46.9	34.8	30.3	47.0	40.8
182	35.8	33.0	33.2	42.4	42.2	42.8	50.6	46.1	36.6	34.0	53.4	49.6

Table 6 Compressive Strength of Concrete (Chemical 3)

Age (days)	Compressive strength (MPa)											
	S3-00-A1	S3-1.8-A1	S3-2.5-A1	S3-00-FA-A1	S3-1.8-FA-A1	S3-2.5-FA-A1	S3-00-FA-H-A1	S3-1.8-FA-H-A1	S3-00-FA-A2	S3-1.8-FA-A2	S3-00-FA-A3	S3-1.8-FA-A3
1	16.9	15.7	16.8	4.6	8.8	8.9	10.3	13.7	5.1	5.5	7.3	6.6
3	31.0	27.2	31.7	23.7	23.4	25.0	22.7	33.2	19.6	18.4	27.5	21.5
7	36.6	35.6	36.6	32.4	31.1	32.8	29.4	40.6	25.9	25.9	38.8	33.0
14	41.4	39.6	39.4	35.2	36.3	37.0	35.3	45.7	30.3	32.4	44.0	38.8
28	43.9	43.1	44.2	42.3	46.1	41.7	41.0	54.4	33.9	36.8	54.5	44.6
91	53.2	49.6	51.0	48.9	56.6	48.5	51.6	62.2	38.1	44.4	63.8	53.0
182	51.9	52.3	…	46.3	58.1	52.8	52.6	63.5	40.7	49.9	71.2	60.9

Table 7 Chloride-Ion Penetrability into Concrete (Chemical 1)

Age (days)	Chloride-ion penetrability (Coulomb)											
	S1-00-A1	S1-1.6-A1	S1-2.1-A1	S1-00-FA-A1	S1-1.6-FA-A1	S1-2.1-FA-A1	S1-00-FA-H-A1	S1-1.6-FA-H-A1	S1-00-FA-A2	S1-1.6-FA-A2	S1-00-FA-A3	S1-1.6-FA-A3
28	2820	2180	1970	1970	1940	1480	1910	1560	2810	2390	3410	3940
56	2090	1810	1630	1020	1220	960	1070	960	1600	1540	1570	1750
182	1580	1470	1150	480	550	570	430	380	720	720	800	850

Table 8. Chloride-Ion Penetrability into Concrete (Chemical 2)

Age (days)	Chloride-ion penetrability (Coulomb)											
	S2-00-A1	S2-1.8-A1	S2-3.0-A1	S2-00-FA-A1	S2-1.8-FA-A1	S2-3.0-FA-A1	S2-00-FA-H-A1	S2-2.0-FA-H-A1	S2-00-FA-A2	S2-1.8-FA-A2	S2-00-FA-A3	S2-1.8-FA-A3
28	5280	4490	3310	4740	2530	3140	2840	3430	3920	3300	3080	4140
56	3210	3690	2750	1880	1290	1780	1310	1800	2100	1910	1960	2450
182	2230	2560	2300	1000	630	850	490	710	960	1070	990	870

Table 9. Chloride-Ion Penetrability into Concrete (Chemical 3)

Age (days)	Chloride-ion penetrability (Coulomb)											
	S3-00-A1	S3-1.8-A1	S3-2.5-A1	S3-00-FA-A1	S3-1.8-FA-A1	S3-2.5-FA-A1	S3-00-FA-H-A1	S3-1.8-FA-H-A1	S3-00-FA-A2	S3-1.8-FA-A2	S3-00-FA-A3	S3-1.8-FA-A3
28	4390	2490	2000	4510	2910	1840	2980	2050	2900	2640	4020	2950
56	3010	1710	1750	2400	1640	980	1750	1090	1470	1620	2440	1630
182	2250	1520	1250	840	650	520	560	410	690	850	790	690

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Fig. 12. Chloride-ion penetrability into Grade A no-ash concrete vs. SRA dosage rate (Chemical 2, Aggregate 1)

Fig. 13. Chloride-ion penetrability into Grade A-FA fly ash concrete vs. age (Chemical 2, Aggregate 1)

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Fig. 20. Chloride-ion penetrability into Grade A-FA fly ash concrete vs. aggregate type (Chemical 2; Aggregates 1, 2, 3)

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Fig. 30. Chloride-ion penetrability into Grade A-FA fly ash concrete vs. aggregate type (Chemical 3; Aggregates 1, 2, 3)

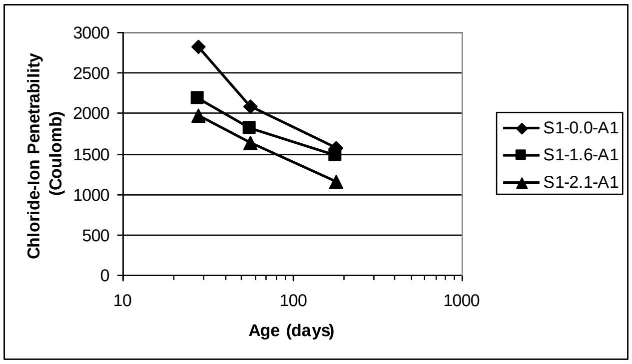


Fig. 1. Chloride-ion penetrability into Grade A no-ash concrete vs. age (Chemical 1, Aggregate 1)

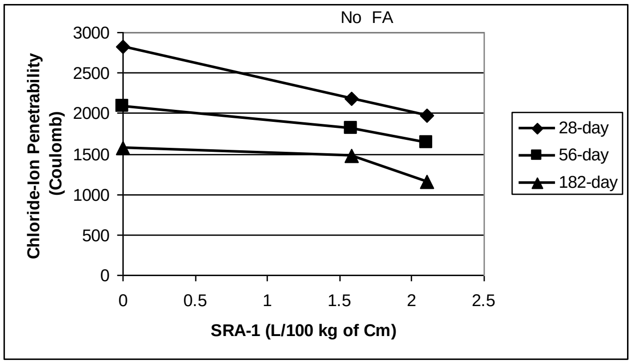


Fig. 2. Chloride-ion penetrability into Grade A no-ash concrete vs. SRA dosage rate (Chemical 1, Aggregate 1)

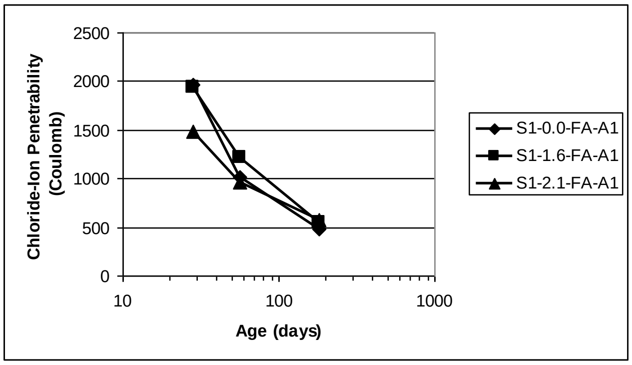


Fig. 3. Chloride-ion penetrability into Grade A-FA fly ash concrete vs. age (Chemical 1, Aggregate 1)

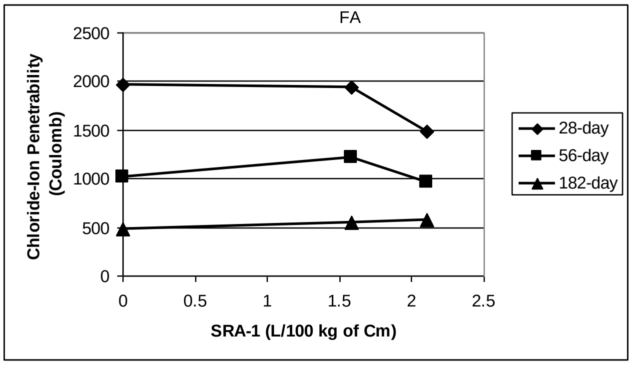


Fig. 4. Chloride-ion penetrability into Grade A-FA fly ash concrete vs. SRA dosage rate (Chemical 1, Aggregate 1)

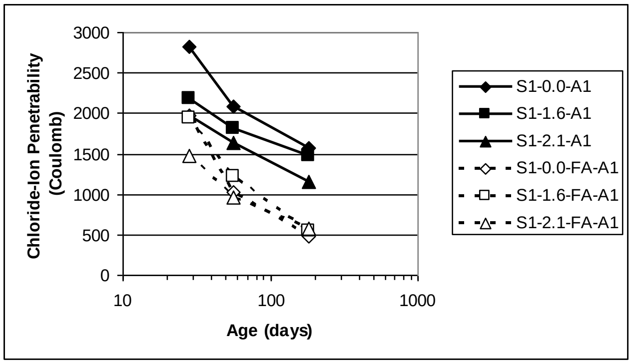


Fig. 5. Chloride-ion penetrability into Grade A no-ash concrete and Grade A-FA fly ash concrete vs. age (Chemical 1, Aggregate 1)

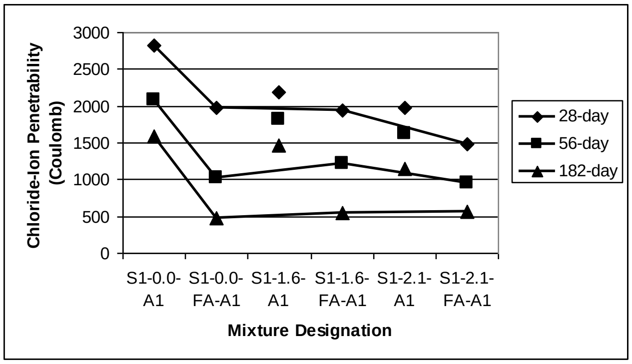
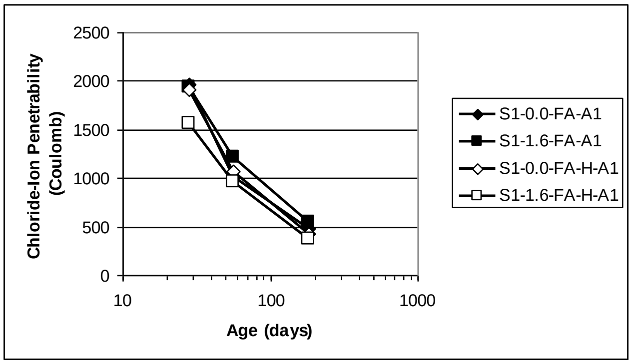


Fig. 6. Chloride-ion penetrability into no-SRA concrete and SRA concrete vs. fly ash content (Chemical 1, Aggregate 1)



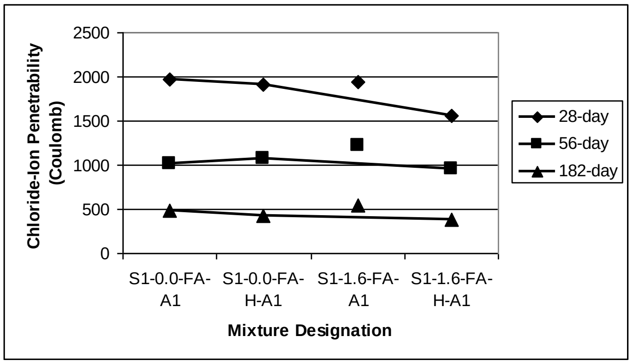
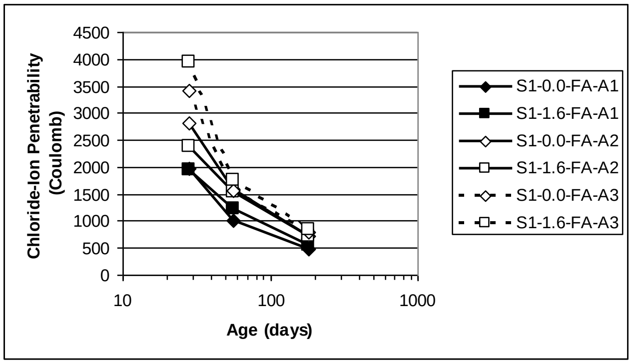


Fig. 7. Chloride-ion penetrability into Grade A-FA fly ash concrete and high-Cm concrete vs. age (Chemical 1, Aggregate 1)

Fig. 8. Chloride-ion penetrability into concrete vs. cementitious materials content (Chemical 1, Aggregate 1)



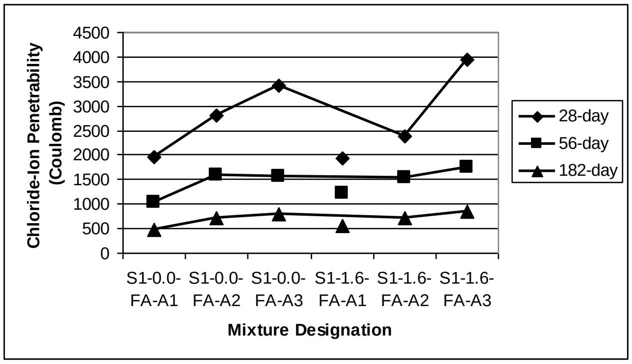
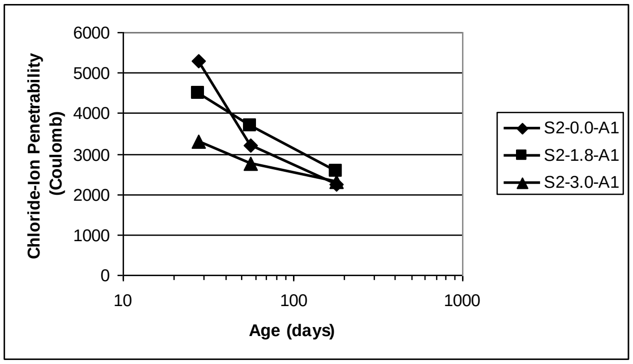


Fig. 9. Chloride-ion penetrability into Grade A-FA fly ash concrete made with A1, A2, A3 vs. age (Chemical 1; Aggregates 1, 2, 3)

Fig. 10. Chloride-ion penetrability into Grade A-FA fly ash concrete vs. aggregate type (Chemical 1; Aggregates 1, 2, 3)



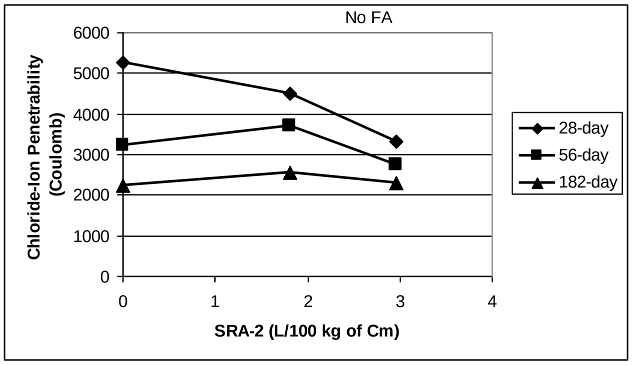


Fig. 11. Chloride-ion penetrability into Grade A no-ash concrete vs. age (Chemical 2, Aggregate 1)

Fig. 12. Chloride-ion penetrability into Grade A no-ash concrete vs. SRA dosage rate (Chemical 2, Aggregate 1)

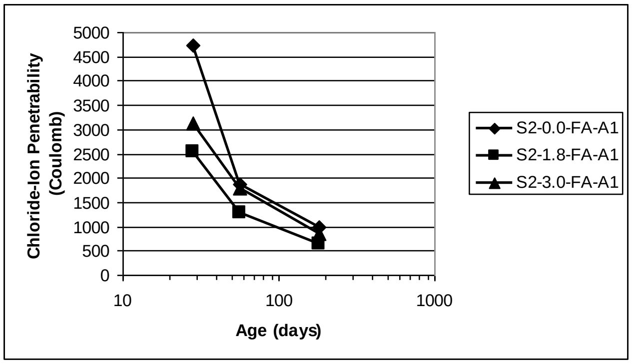


Fig. 13. Chloride-ion penetrability into Grade A-FA fly ash concrete vs. age (Chemical 2, Aggregate 1)

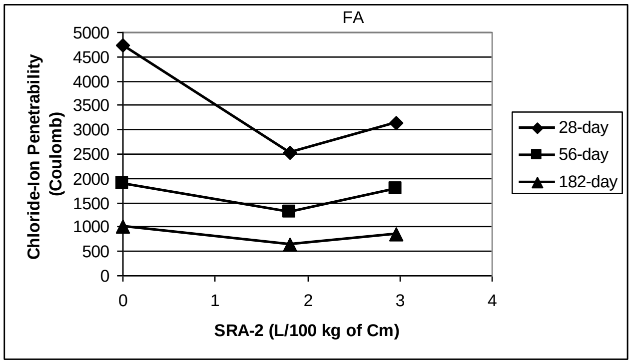


Fig. 14. Chloride-ion penetrability into Grade A-FA fly ash concrete vs. SRA dosage rate (Chemical 2, Aggregate 1)

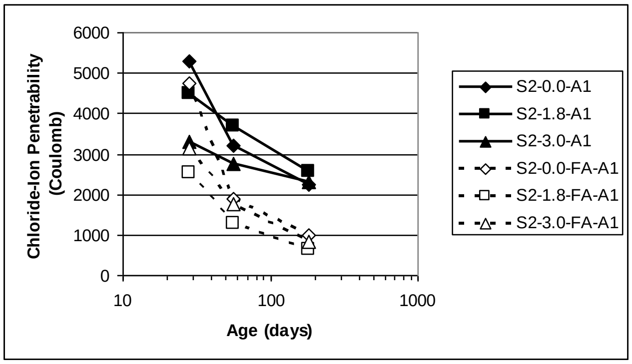


Fig. 15. Chloride-ion penetrability into Grade A no-ash concrete and Grade A-FA fly ash concrete vs. age (Chemical 2, Aggregate 1)

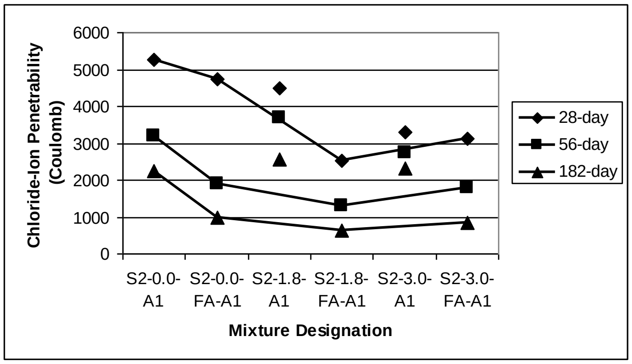


Fig. 16. Chloride-ion penetrability into no-SRA concrete and SRA concrete vs. fly ash content (Chemical 2, Aggregate 1)

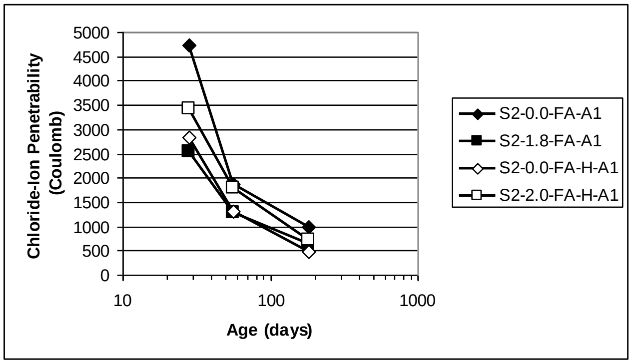


Fig. 17. Chloride-ion penetrability into Grade A-FA fly ash concrete and high-Cm concrete vs. age (Chemical 2, Aggregate 1)

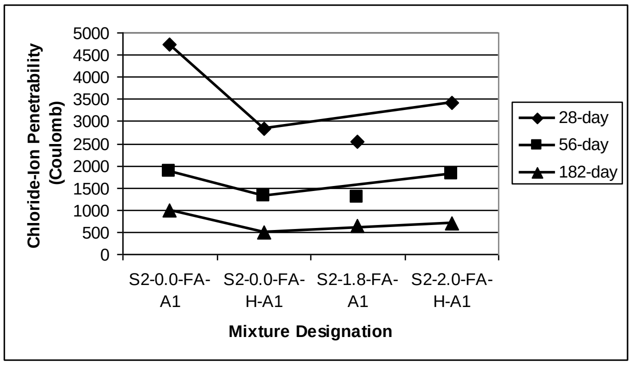
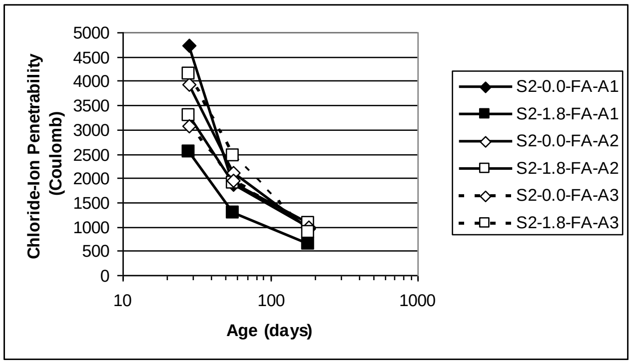


Fig. 17. Chloride-ion penetrability into concrete vs. cementitious materials content (Chemical 2, Aggregate 1)



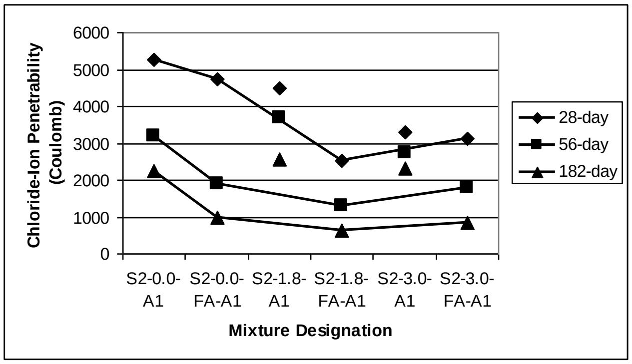
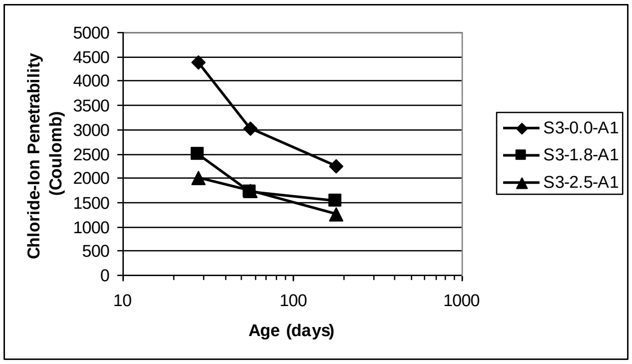


Fig. 19. Chloride-ion penetrability into Grade A-FA fly ash concrete made with A1, A2, A3 vs. age (Chemical 2; Aggregates 1, 2, 3)

Fig. 20. Chloride-ion penetrability into Grade A-FA fly ash concrete vs. aggregate type (Chemical 2; Aggregates 1, 2, 3)



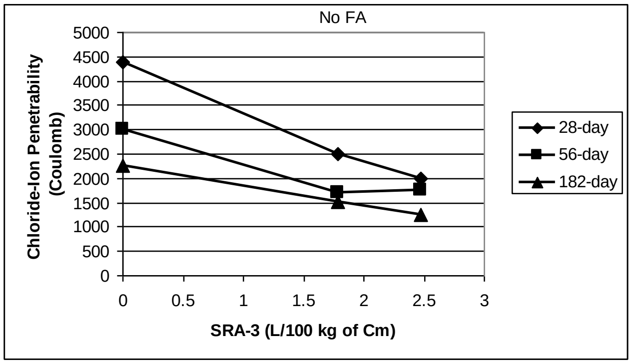
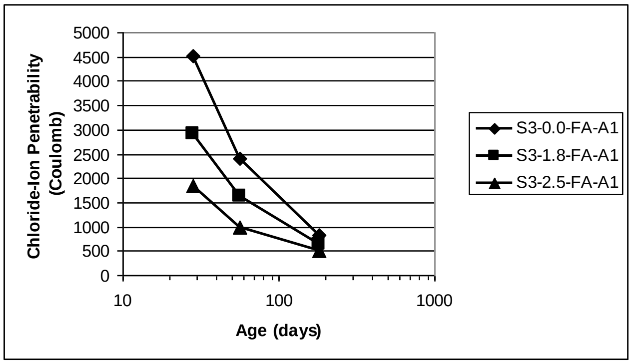


Fig. 21. Chloride-ion penetrability into Grade A no-ash concrete vs. age (Chemical 3, Aggregate 1)

Fig. 22. Chloride-ion penetrability into Grade A no-ash concrete vs. SRA dosage rate (Chemical 3, Aggregate 1)



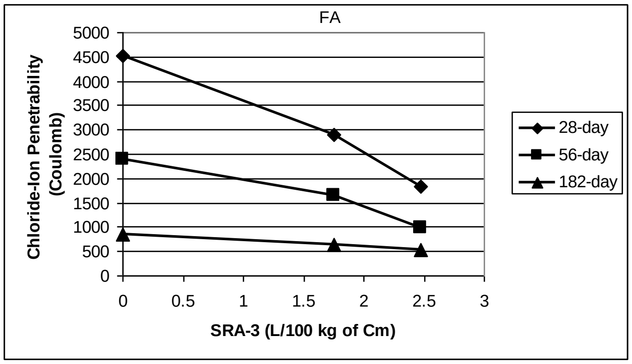
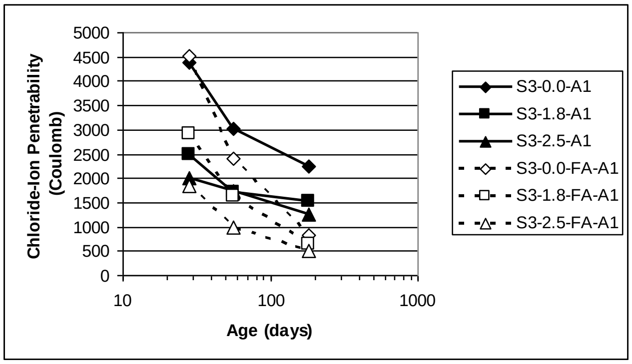


Fig. 23. Chloride-ion penetrability into Grade A-FA fly ash concrete vs. age (Chemical 3, Aggregate 1)

Fig. 24. Chloride-ion penetrability into Grade A-FA fly ash concrete vs. SRA dosage rate (Chemical 3, Aggregate 1)



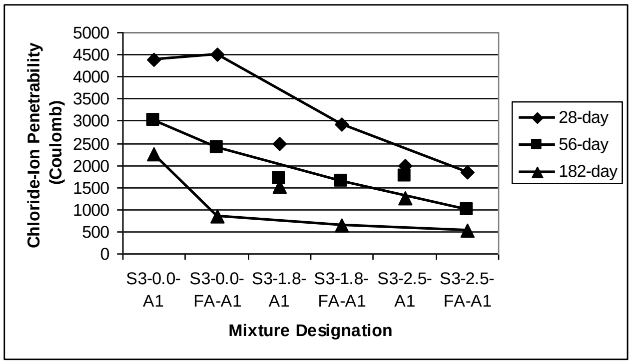
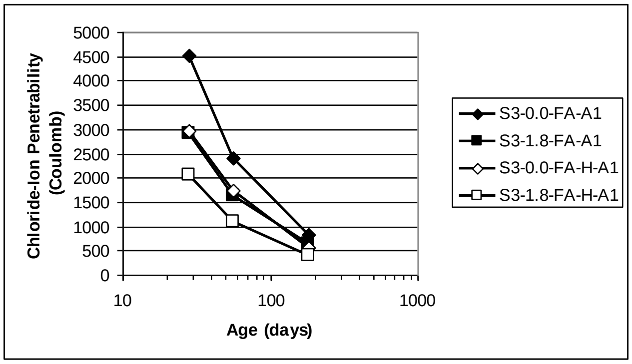


Fig. 25. Chloride-ion penetrability into Grade A no-ash concrete and Grade A-FA fly ash concrete vs. age (Chemical 3, Aggregate 1)

Fig. 26. Chloride-ion penetrability into no-SRA concrete and SRA concrete vs. fly ash content (Chemical 3, Aggregate 1)



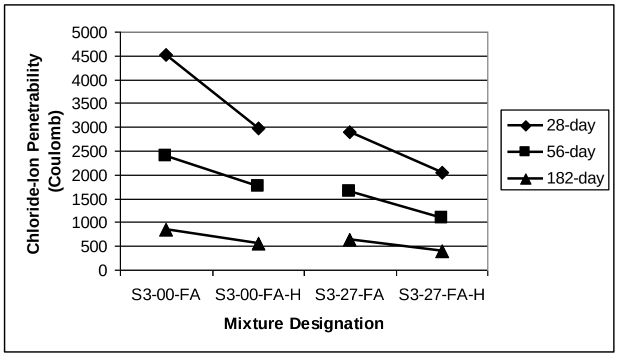
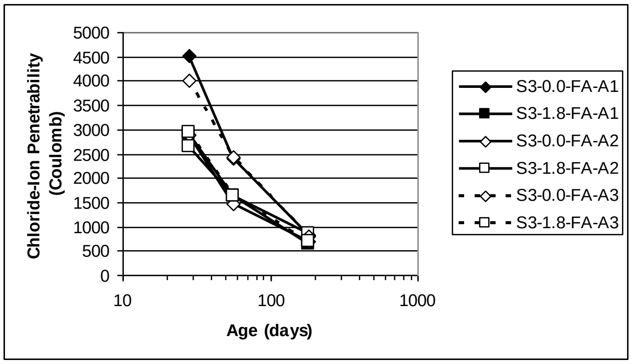


Fig. 27. Chloride-ion penetrability into Grade A-FA fly ash concrete and high-Cm concrete vs. age (Chemical 3, Aggregate 1)

Fig. 28. Chloride-ion penetrability into concrete vs. cementitious materials content (Chemical 3, Aggregate 1)



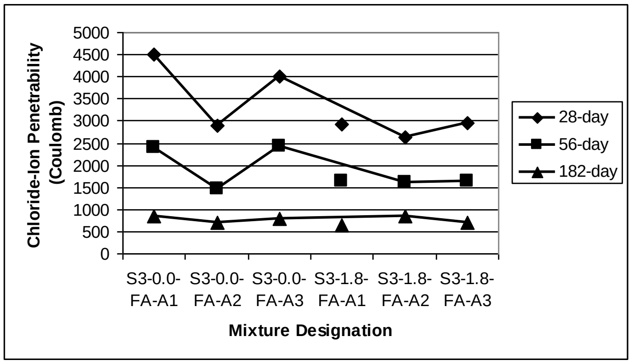


Fig. 29. Chloride-ion penetrability into Grade A-FA fly ash concrete made with A1, A2, A3 vs. age (Chemical 3; Aggregates 1, 2, 3)

Fig. 30. Chloride-ion penetrability into Grade A-FA fly ash concrete vs. aggregate type (Chemical 3; Aggregates 1, 2, 3)