Investigation on the Parameters Affecting the De-Icing Salt Scaling Resistance of Fly Ash Concrete

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REPORT SUMMARY

In scaling of concrete by de-icing salts, the mortar near the surface flakes or peels away. This report presents the results of an R&D laboratory study to examine the scaling of high ash content concrete from the use of salts used routinely in cold climates to melt ice and snow on roads and sidewalks.

Background

The use of de-icing salts on roads, highways, and sidewalks, common for many years, has caused problems with the formation of scale on concrete surfaces. The mechanism for this damaging reaction in concrete is not well understood. Fly ash has been used in recent years as a partial replacement of portland cement. Although the fly ash has provided many advantages in terms of cost, workability during placement, and reduction of thermal stresses during curing, it has also been shown to be less resistant to salt-scaling. Understanding this phenomenon and developing mitigation methods could increase the applications for fly ash in highway pavement construction.

Objective

To understand why fly ash reduces the resistance of concrete to de-icing salt scaling when used in large amounts in air-entrained concrete.

Approach

The project team developed a laboratory test plant to study the effect of water to cementitious (w/c) ratio, fly ash content, fly ash type, and different conditions of casting and curing on the de-icing salt scaling of concrete. The team made fourteen air-entrained concrete mixtures, ranging from zero to 58% fly ash. The w/c ratios ranged from 0.32 to 0.45. Two ASTM Class F ashes and one ASTM Class C fly ash were utilized. The team evaluated the resistance of the concrete to de-icing salts on concrete slabs using the total mass of concrete scaling residue and a visual rating system after 50 cycles of freezing and thawing in a 3% NaCl solution.

Results

There are conflicting published data concerning the extent to which fly ash impairs the scaling resistance of concrete. Testing results indicate that the type and amount of fly ash used and w/c ratio of the concrete affect the de-icing salt scaling resistance of the concrete. In general, the resistance to scaling decreases with increasing amounts of fly

ash and water-to-cementitious materials ratio. The curing conditions of the concrete were also found to be a significant factor in scaling resistance. The longer the duration of the drying period before testing, the greater the salt-scaling. The microstructure of the curing cement paste at the onset of the freezing and thawing cycle appears to affect the de-icing salt-scaling of the concrete. Use of curing compounds to control the drying of the concrete greatly improved the scaling resistance of all the concretes but was especially beneficial to the fly ash concretes.

EPRI Perspective

As expected, the results showed that there are several interrelated factors affecting the salt scaling of concretes containing fly ash. Under field conditions, curing of concrete is not always a high priority and is often not done according to specifications. In practice, there is little control over the drying of concrete. The use of curing compounds to seal in the moisture of the concrete during the critical curing cycle can significantly improve the scaling resistance without relying on hit-or-miss moist curing. It should be noted that the ASTM test used for the evaluation is quite a bit more severe than actual field exposures to road salts.

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Interest Categories

Waste and water management

Key Words

Salt-scaling

Coal fly ash

Concrete curing

Concrete durability

High-volume fly ash concrete

ABSTRACT

In many countries, de-icing chemicals such as sodium chloride are used routinely to melt ice and snow on highways, roads, and sidewalks. As a result, the scaling of concrete caused by the application of such de-icing chemicals has been a major concern for many years.

Fly ash is being used increasingly in concrete in recent years either to save cement or to improve properties of concrete. However, many laboratory studies have shown that in many instances the use of fly ash in large quantities (>25%) in air-entrained concrete reduces the resistance of concrete to the de-icing salt scaling substantially. There are conflicting published data concerning the extent to which fly ash impairs the scaling resistance of concrete, due in part to the variation in the materials used and differences in the curing regimes, and also due to the poor reproducibility of test methods used.

The primary objective of this study is to investigate the effect of the water-to-cementitious materials ratio (W/CM), fly ash content, fly ash type, and different conditions of casting and curing on the de-icing salt scaling of concrete, and to understand why fly ash when used in large amounts in air-entrained concrete reduces the resistance of concrete to the de-icing salt scaling.

Fourteen air-entrained concrete mixtures incorporating 0, 25, 35 and 58 per cent fly ash, and having W/CM ranging from 0.32 (high-volume fly ash concrete) to 0.45 were made in this study. Three fly ashes, two ASTM Class F and one Class C, were included in this investigation.

In general, the resistance to the de-icing salt scaling decreases with increasing amounts of fly ash and increasing W/CM. Concretes incorporating up to 35% Belews Creek fly ash and having a W/CM of 0.40 or less performed well in the standard scaling test. For concrete incorporating 25% Pleasant Prairie fly ash (ASTM Class C), concrete did not perform satisfactorily when the W/CM ≥0.40. For concrete incorporating 25% Montour fly ash (ASTM Class F), the concrete had severe scaling regardless of the W/CM investigated. Extended moist-curing periods beyond 14 days do not insure increased resistance to de-icing salt scaling for concrete. The amount of scaling residue increased significantly with an increase in the duration of the drying period, especially for the fly ash concretes. The use of the curing compounds greatly improved the scaling resistance of all concretes tested but was more beneficial for the fly ash concretes. The microstructure of the cement paste at the onset of the freezing and thawing appears to affect the de-icing salt scaling of the concrete.

ACKNOWLEDGMENTS

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INTRODUCTION

In many countries, de-icing chemicals such as sodium chloride are used routinely to melt ice and snow on highways, roads, and sidewalks. As a result, the scaling of concrete caused by the application of such de-icing chemicals has been a major concern for many years.

In the de-icing salt scaling of concrete, the mortar near the surface flakes or peels away. It is primarily a surface phenomenon in contrast to the internal cracking of concrete in freezing and thawing cycling when the bulk of the concrete is affected. It is generally agreed that the deterioration caused by the de-icing chemicals is mostly physical in nature, and that the chemical reactions of the salts with the cement hydration products play only a secondary role in the deterioration mechanisms. The published data also indicate that, regardless of the type of the de-icing chemicals used, relatively low concentration of de-icing chemicals in the range of 2 to 5% produces more surface scaling than higher concentrations or pure water. Whereas proper air entrainment adequately protects mature concrete made with sound aggregates against damage due to freezing and thawing cycling, air entrainment, in general, does not completely prevent surface scaling. Many researchers have tried to explain the mechanism of the damage caused by the de-icing salt scaling, but there are several issues which remain unexplained [1,2].

Fly ash is being used increasingly in concrete in recent years either to save cement or to improve properties of concrete. The incorporation of fly ash in concrete reduces its permeability and improves its long-term strength and durability. When exposed to freezing and thawing cycles in the presence of de-icing salts, concrete with a water-to-cementitious materials ratio (W/CM) lower than 0.45 and incorporating up to 25% fly ash generally performs satisfactorily. However, many laboratory studies have shown that in many instances the use of fly ash in large quantities (>25%) in air-entrained concrete reduces the resistance of concrete to the de-icing salt scaling substantially [3-7]. Bilodeau et al. [8, 9] found that fly ash, both Class F and Class C, when present in large proportions (56% by weight of the total cementitious materials), results in concrete with poor resistance to the de-icing salts in the laboratory tests, even though the concrete performs satisfactorily in the field under de-icing salt scaling exposure [10]. The reasons for this have not been established.

There are conflicting published data concerning the extent to which fly ash impairs the scaling resistance of concrete, due in part to the variation in the materials used and differences in the curing regimes, and also due to the poor reproducibility of test methods used. In general, however, the scaling does seem to increase with increasing amounts of fly ash in concrete in laboratory tests.

The primary objective of this study is to investigate the effect of the water-to-cementitious materials ratio, fly ash content, fly ash type, and different conditions of casting and curing on the de-icing salt scaling of concrete, and to understand why fly ash when used in large amounts in air-entrained concrete reduces the resistance of concrete to the de-icing salt scaling.

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DESCRIPTION OF THE STUDY

Scope

Fourteen air-entrained concrete mixtures were made in this study. Reference concrete without fly ash, concrete incorporating 25 and 35% fly ash, and a high-volume fly ash concrete mixture with 58% fly ash were made. The water-to-cementitious materials ratio (W/CM) of the mixtures ranged from 0.32 (high-volume fly ash concrete) to 0.45. Three fly ashes, two ASTM Class F and one Class C, were included in this investigation.

The properties of the fresh concrete determined included the unit weight, slump, air content, and bleeding. A number of cylinders and prisms were used for the determination of compressive and flexural strengths of the concrete.

The resistance of the concrete to the de-icing salt scaling was evaluated on concrete slabs using the total mass of the scaling residue and the visual rating after 50 cycles of freezing and thawing in a 3% NaCl solution. Most slabs were cast in horizontal moulds and finished using a wood trowel but a number of slabs were cast in vertical moulds. The slabs were either moist cured or cured using a curing compound before being subjected to drying prior to the scaling test, and different moist-curing and air-drying periods were used. For selected concrete slabs, the water absorption of the testing surface after 6 hours was determined prior to the de-icing salt scaling test.

Research Significance

The intent of this study was to determine how, and possibly why different factors affect the de-icing salt scaling resistance of fly ash concrete. Various conditions of testing for the laboratory specimens, not necessarily representing the actual field conditions, were used to analyze the effect of several factors on the performance of the concrete in the scaling test. Once those factors are better understood, it is possible to determine whether they can potentially affect the field performance. The ultimate objective of the study is to make recommendations to the construction engineer of proper procedures to be followed for obtaining satisfactory performance of fly ash concrete in the field when exposed to de-icing salts.

Materials

Cement

ASTM Type I portland cement was used. Its physical properties and chemical composition are given in Table 2-1.

Table 2-1
Physical properties and chemical analysis of the cement and fly ashes

	ASTM Type I Cement	Fly Ash		
		Belews Creek	Pleasant Prairie	Montour
Physical Properties				
Specific gravity	3.13	2.47	2.62	2.34
Fineness				
- passing 45 ✚m, %	92.9	79.8	80.0	66.8
- specific surface, Blaine, m^2/kg	386	264	422	241
Compressive strength of 51-mm cubes, MPa				
- 7 days	35.0	-	-	-
- 28 days	42.6	-	-	-
Pozzolanic activity index, %				
- 7 days	-	86.3	94.9	83.1
- 28 days	-	91.3	101.4	79.8
Chemical Analysis, %				
Silicon dioxide (SiO2)	20.56	56.96	33.90	49.48
Aluminum oxide (Al2O3)	4.08	29.72	19.36	26.81
Ferric oxide (Fe2O3)	2.82	5.95	6.10	14.59
Calcium oxide (CaO)	64.4	1.44	28.24	1.44
Magnesium oxide (MgO)	2.85	1.01	4.82	0.82
Sodium oxide (Na2O)	0.35	0.26	1.88	0.27
Potassium oxide (K2O)	0.72	2.32	0.40	2.32
Equivalent alkalis (Na2O+0.658K2O)	0.82	1.79	2.14	1.80
Phosphorous oxide (P2O5)	0.24	0.22	1.46	0.40
Titanium oxide (TiO2)	0.20	1.55	1.67	1.37
Sulphur trioxide (SO3)	3.00	0.46	2.98	0.64
Loss on ignition	1.42	0.72	0.25	3.73
Bogue Potential Compound Composition				
Tricalcium silicate C3S	66	-	-	-
Dicalcium silicate C2S	9	-	-	-
Tricalcium aluminate C3A	6	-	-	-
Tetracalcium aluminoferrite C4AF	9	-	-	-

Conversion factor: 1 MPa = 145 psi

Fly Ash

The fly ashes used were obtained from Belews Creek Generating Station, Duke Power, North Carolina, Pleasant Prairie Power Plant, Wisconsin Electric Power Company, Wisconsin, and Montour Power Plant, Pennsylvania Power & Light Company, Pennsylvania. The Belews Creek fly ash was produced with eastern bituminous coal. The Pleasant Prairie power plant uses western sub-bituminous coal from the Powder River Basin, and the Montour fly ash was produced with bituminous coal from central Pennsylvania. The physical properties and chemical compositions of the fly ashes are also given in Table 2-1.

Both Belews Creek and Montour fly ashes were ASTM Class F type, with a CaO content 1.4% each and the specific surface (Blaine) of the fly ashes was 264 and 241 m^2/kg, respectively.

Pleasant Prairie fly ash, met the general requirements of ASTM Class C ash, had a CaO content of 28.2% and a specific surface of 422 m^2/kg (Blaine).

Aggregates

The coarse aggregate used was crushed granite with a maximum nominal size of 19 mm (3/4 in.), and the fine aggregate was natural sand from the Ottawa region. Both the coarse and fine aggregates were separated into different size fractions and recombined to a specified gradation shown in Table 2-2. The specific gravities of the coarse and fine aggregates were 2.72 and 2.70, respectively; the corresponding values for water absorption were 0.5 and 0.8 percent, respectively (Table 2-3). The aggregates meet the requirements of ASTM C 33.

Table 2-2
Grading of aggregates

Coarse Aggregate			Fine Aggregate		
Sieve size		Cumulative percentage retained	Sieve size		Cumulative percentage retained
mm	(in)		mm		
19.0	(3/4)	0	4.75	(No.4)	0
12.7	(1/2)	30	2.36	(No.8)	10.0
9.5	(3/8)	70	1.18	(No.16)	32.5
4.75	(No.4)	100	0.60	(No.30)	57.5
			0.30	(No.50)	80.0
			0.15	(No.100)	94.0
			pan		100.0

Table 2-3
Physical properties of aggregates

	Coarse Aggregate	Fine Aggregate
Specific gravity	2.72	2.70
Absorption	0.5	0.8

Superplasticizer

A sulfonated naphthalene formaldehyde based superplasticizer, which meets the requirements of ASTM C 494 Type F, was used for most of the concrete mixtures. The superplasticizer is a dark brown solution containing 42 percent solids.

Air-Entraining Admixture

A multicomponent synthetic resin type of air-entraining admixture, which meets the requirements of ASTM C 260, was used in all concrete mixtures.

Curing Compounds

Two white pigmented resin-based curing compounds[1] from different manufacturers (designated as "I" and "II") and one water-based polymer and wax emulsion curing and sealing compound[2] designated as "III") were used for the curing of some of the slabs, and were applied according to manufacturer's instructions. The curing compounds "I" and "II" meet the requirements of ASTM C 309, Type 2, Class B, and the curing compound "III" meets the requirements of ASTM C 309 Type 1.

Mixture Proportions

The proportioning of the concrete mixtures is summarized in Tables 2-4 and 2-5. A total of fourteen concrete mixtures were made, and for some of them (mixtures 1, 2, 4, 5, 7 and 8) two batches were needed for casting a sufficient number of specimens. Two reference mixtures without fly ash were made with water-to-cement ratios (W/C) of 0.40 and 0.45. Six fly ash concrete mixtures were made with Belews Creek fly ash: these consisted of three mixtures incorporating 25 percent fly ash with water-to-cementitious materials ratios (W/CM) of 0.35, 0.40 and 0.45, two mixtures with 35 percent fly ash at W/CM of 0.35 and 0.40, and a high-volume fly ash concrete incorporating 58 percent fly ash, at a W/CM of 0.32. Three mixtures were made

[1] "I" - Sealtight 1220, W. R. Meadows of Canada Ltd.
"II" - Enviocure White 500, Vexcon Chemicals.
[2] "III" - Masterkure 200W, Master Builder Inc.

with each of Pleasant Prairie and Montour fly ashes at W/CM of 0.35, 0.40, and 0.45, and with 25 percent fly ash as partial replacement for cement.

Table 2-4
Proportions of the concrete mixtures (SI units)

Mixture No.	W/CM*	Water, kg/m^3	Cement, kg/m^3	Fly Ash			CA** kg/m^3	FA** kg/m^3	AEA[#] mL/m^3	SP[##] L/m^3
				Source	%	kg/m^3				
1A	0.40	162	404	-	0	0	1068	712	145	0.3
1B	0.40	161	403	-	0	0	1061	704	120	0.3
2A	0.45	168	372	-	0	0	1048	700	80	0
2B	0.45	168	373	-	0	0	1049	701	80	0
3	0.35	142	302	BC[(1)]	25	101	1080	719	195	2.8
4A	0.40	158	296	BC	25	99	1025	685	120	0
4B	0.40	161	301	BC	25	101	1045	698	120	0
5A	0.45	170	283	BC	25	95	1047	699	80	0
5B	0.45	169	281	BC	25	94	1039	695	80	0
6	0.35	139	258	BC	35	139	1059	705	200	2.5
7A	0.40	163	265	BC	35	143	1055	704	100	0
7B	0.40	161	262	BC	35	141	1035	687	100	0
8A	0.32	120	156	BC	58	217	1099	751	330	3.3
8B	0.32	119	157	BC	58	217	1102	753	330	3.3
9	0.35	143	302	PP[(2)]	25	101	1077	719	190	3.0
10	0.40	161	303	PP	25	101	1049	701	100	0
11	0.45	170	283	PP	25	95	1048	701	80	0
12	0.35	141	300	M[(3)]	25	100	1064	709	300	2.4
13	0.40	161	302	M	25	101	1046	699	200	0.9
14	0.45	159	264	M	25	88	1049	707	200	0

* Water-to-cementitious materials ratio

** CA: Coarse aggregate, and FA: Fine aggregate

AEA: Air-entraining admixture

SP: Superplasticizer

(1) BC: Belews Creek fly ash

(2) PP: Pleasant Prairie fly ash

(3) M: Montour fly ash

The percentage replacement of cement by fly ash in the concrete was on the weight basis. All the mixtures were air-entrained, with the target air content of 6 ± 1 percent. A superplasticizer was used in some mixture.

Table 2-5
Proportions of the concrete mixtures (English units)

Mixture No.	W/CM*	Water, lb/yd^3	Cement, lb/yd^3	Fly Ash			CA** lb/yd^3	FA** lb/yd^3	AEA[#] oz/yd^3	SP[##] oz/yd^3
				Source	%	lb/yd^3				
1A	0.40	273	681	-	0	0	1800	1200	3.8	8
1B	0.40	271	679	-	0	0	1788	1187	3.1	8
2A	0.45	283	627	-	0	0	1766	1180	2.1	0
2B	0.45	283	629	-	0	0	1768	1182	2.1	0
3	0.35	239	509	BC(1)	25	170	1820	1212	5.1	72
4A	0.40	266	499	BC	25	167	1728	1155	3.1	0
4B	0.40	271	507	BC	25	170	1761	1176	3.1	0
5A	0.45	287	477	BC	25	160	1765	1178	2.1	0
5B	0.45	285	474	BC	25	158	1751	1171	2.1	0
6	0.35	234	435	BC	35	234	1785	1188	5.2	65
7A	0.40	275	447	BC	35	241	1778	1187	2.6	0
7B	0.40	271	442	BC	35	238	1744	1158	2.6	0
8A	0.32	202	263	BC	58	366	1852	1266	8.5	85
8B	0.32	201	265	BC	58	366	1857	1269	8.5	85
9	0.35	241	509	PP(2)	25	170	1815	1212	4.9	78
10	0.40	271	511	PP	25	170	1768	1182	2.6	0
11	0.45	287	477	PP	25	160	1766	1182	2.1	0
12	0.35	238	506	M(3)	25	169	1793	1195	7.8	62
13	0.40	271	509	M	25	170	1763	1178	5.2	23
14	0.45	268	445	M	25	148	1768	1192	5.2	0

* Water-to-cementitious materials ratio

** CA: Coarse aggregate, and FA: Fine aggregate

AEA: Air-entraining admixture

SP: Superplasticizer

(1) BC: Belews Creek fly ash

(2) PP: Pleasant Prairie fly ash

(3) M: Montour fly ash

For all the mixtures, the graded coarse and fine aggregates were weighed in a room-dry condition. In order to saturate the aggregates, the coarse fraction was then immersed in water for 24 hours, and a predetermined amount of water was added to the sand. The concrete mixtures were made in a laboratory counter-current mixer with the fly ash added as a separate ingredient.

Preparation and Casting of Test Specimens

Fifteen 102x203-mm (4x8 in.) cylinders, two 102x76x400-mm (4x3x16 in.) prisms and a number of 300x300x75-mm (12x12x3 in.) slabs were cast from batch A of each mixture. Three cylinders and an additional number of slabs were also cast from the batch B of mixtures 1, 2, 4, 5, 7 and 8.

The cylinders and prisms were cast in two layers, each layer being consolidated using a vibrating table. Most of the slabs were cast horizontally, but some slabs were cast using vertical moulds. The slabs cast horizontally were cast in one layer, and were consolidated by rodding. The surface of these slabs was finished using a wood trowel, and when the bleeding of the concrete had stopped, the surface was brushed gently using a paint brush. The slabs cast vertically were cast in two layers, and consolidated by rodding. The surface of the slabs cast vertically that was to be tested for scaling resistance was cast against the formwork; it was therefore not subjected to any finishing nor brushing. After casting, all the moulded specimens were covered with plastic sheets and water-saturated burlap, and left in the casting room for 24 hours except for the slabs that were cured with curing compounds. The specimens were then demoulded and transferred to the moist-curing room at 23 ± 1.7°C (73.4 ± 3°F) and 100 percent humidity until required for testing. For the slabs cured with curing compounds, the compound was sprayed on the horizontal concrete surface immediately after the surface bleeding water had disappeared. After demoulding at 24 hours, the curing compound was sprayed on the remaining surfaces of the concrete slabs.

Testing of Specimens

The properties of fresh concrete including the slump, air content, unit weight, and bleeding were determined following ASTM C 143, C 231, C 138, and C 232, respectively.

The fifteen cylinders from batch A were tested in compression at various ages up to 91 days, and the three cylinders from batch B were tested in compression at the age of 28 days only. The prisms were tested in flexure at 14 days.

The moist-cured horizontally cast slabs from each mixture were subjected to different moist-curing and air-drying periods before being tested for the de-icing salt scaling resistance. The duration of moist curing ranged from 7 to 56 days, and that of air drying from 0 to 14 days. The slabs treated with the curing compounds were cured for 14 days in the laboratory air, and the curing compounds were then removed by vigourous brushing. Following this, the slabs were subjected to 14 days of additional air drying. The slabs cast vertically were subjected to 14 days of moist curing followed by 14 days of air drying except that the two vertically cast slabs from mixture 6 were cured using a curing compound. After the drying period, the surface of the slabs was ponded with a known quantity of 3 percent sodium chloride solution, and covered with a plastic sheet to prevent evaporation. After six hours, the solution from the slabs was collected and weighed to determine the surface absorption of the concrete slabs. After this, the slabs were once again covered with the sodium chloride solution and placed in a freezer at -18 ± 2.0°C (0 ± 4°F) for 16 to 18 hours. At the end of this period, the slabs were removed from the freezer and left in the laboratory air at 23 ± 1.7°C (73.4 ± 3°F) for 6 to 8 hours. This cycle of freezing and thawing was repeated daily except during the weekends when the slabs were kept frozen. At the end of each 5 cycles, the surface of the slabs was flushed off thoroughly, the scaling residue was collected, dried and weighed, and the slabs were ponded with a fresh sodium chloride solution. The slabs were subjected to a total of 50 cycles of freezing and thawing. At the end of the test, the surface of the slabs was rated visually, and a photographic record of the surface of the slabs was taken. The test used for the de-icing salt scaling resistance was very similar to the ASTM C 672 test method.

3

DISCUSSION OF TEST RESULTS

Properties of the Fresh Concrete

The properties of the fresh concrete are given in Tables 3-1 and 3-2.

Table 3-1
Properties of the Fresh Concrete (SI units)

Mixture No.	W/CM	Fly Ash		Temperature, °C	Unit Weight, kg/m³	Slump, mm	Air Content, %	Bleeding, %*
		Source	%					
1A	0.40	-	0	23.0	2327	70	6.3	0.3
1B	0.40	-	0	18.0	2327	65	5.6	-
2A	0.45	-	0	19.5	2285	90	6.7	1.3
2B	0.45	-	0	17.0	2299	140	6.6	-
3	0.35	BC	25	24.0	2327	120	6.5	0.2
4A	0.40	BC	25	17..0	2243	110	7.4	2.0
4B	0.40	BC	25	19.0	2327	90	5.5	-
5A	0.45	BC	25	20.0	2285	145	5.3	2.0
5B	0.45	BC	25	18.0	2299	165	6.0	-
6	0.35	BC	35	24.0	2285	150	7.0	0.6
7A	0.40	BC	35	25.0	2313	160	5.7	3.2
7B	0.40	BC	35	17.5	2299	115	5.8	-
8A	0.32	BC	58	23.0	2383	80	5.2	0
8B	0.32	BC	58	21.0	2369	95	5.2	-
9	0.35	PP	25	20.0	2369	115	5.6	0.3
10	0.40	PP	25	16.0	2299	90	5.5	1.6
11	0.45	PP	25	17.0	2327	175	5.5	3.6
12	0.35	M	25	20.0	2355	75	6.2	0.7
13	0.40	M	25	17.0	2327	65	5.2	1.1
14	0.45	M	25	17.0	2257	100	6.8	2.7

* Bleeding; % of the net mixing water within specimen

The temperature of the fresh concrete ranged from 17 to 25°C (63 to 77°F), the unit weight from 2243 to 2383 kg/m^3 (3781 to 4017 lb/yd^3) and the slump from 65 to 175 mm (2.5 to 7 in.). The air content ranged from 5.2 to 7.4%, and, in general, this range of entrained air in concrete is adequate to produce proper air-void parameters to make concrete durable to freezing and thawing cycling. The bleed water as a percentage of total mixing water ranged from 0 to 3.6%, and increased with an increase in the water-to-cementitious materials ratio and the fly ash content. All the concrete mixtures had satisfactory flow characteristics. From Tables 2-4/2-5 and 3-1/3-2, it seems that the quantities of the superplasticizer and air-entraining admixture required were affected by the type of fly ash used and the water-to-cementitious materials ratio.

Table 3-2
Properties of the fresh concrete (English units)

Mixture No.	W/CM	Fly Ash		Temperature, °F	Unit Weight, lb/yd^3	Slump, in.	Air Content, %	Bleeding, %*
		Source	%					
1A	0.40	-	0	73	3922	2.75	6.3	0.3
1B	0.40	-	0	64	3922	2.5	5.6	-
2A	0.45	-	0	67	3851	3.5	6.7	1.3
2B	0.45	-	0	63	3875	5.5	6.6	-
3	0.35	BC	25	75	3922	4.75	6.5	0.2
4A	0.40	BC	25	63	3781	4.25	7.4	2.0
4B	0.40	BC	25	66	3922	3.5	5.5	-
5A	0.45	BC	25	68	3851	5.75	5.3	2.0
5B	0.45	BC	25	64	3875	6.5	6.0	-
6	0.35	BC	35	75	3851	6.0	7.0	0.6
7A	0.40	BC	35	77	3899	6.25	5.7	3.2
7B	0.40	BC	35	64	3875	4.5	5.8	-
8A	0.32	BC	58	73	4017	3.25	5.2	0
8B	0.32	BC	58	70	3993	3.75	5.2	-
9	0.35	PP	25	68	3993	4.5	5.6	0.3
10	0.40	PP	25	61	3875	3.5	5.5	1.6
11	0.45	PP	25	63	3922	7.0	5.5	3.6
12	0.35	M	25	68	3969	3.0	6.2	0.7
13	0.40	M	25	63	3922	2.5	5.2	1.1
14	0.45	M	25	63	3804	4.0	6.8	2.7

* Bleeding; % of the net mixing water within specimen

Compressive and Flexural Strengths

The compressive strength of the concrete at different ages is given in Tables 3-3 and 3.4, and illustrated in Fig. 3-1 to 3-3. For each W/CM, the compressive strength at early ages of the concrete made with Belews Creek and Montour fly ashes was lower than that of the reference concrete whereas it was similar to or slightly higher than that of the reference concrete of the same W/CM at later ages (56 and 91 days). The concrete made with the Pleasant Prairie fly ash showed the highest compressive strength at all ages and for each W/CM. The high-volume fly ash concrete mixture made with the Belews Creek fly ash showed higher compressive strength than that of the reference concretes at the age of 14 days and beyond. In general, the data show that, at the time of exposure to the de-icing salt scaling test, the fly ash concrete have reached compressive strength values somewhat similar to that of the reference concrete.

Table 3-3
Mechanical properties of the hardened concrete (SI units)

Mixture No.	W/CM	Fly Ash		Density,* kg/m^3	Compressive Strength, MPa					Flexural Strength at 14 d, MPa
		Source	%		7 d	14 d	28 d	56 d	91 d	
1A	0.40	-	0	2357	31.0	32.4	38.1	39.2	42.5	5.8
1B	0.40	-	0	2375	-	-	34.8	-	-	-
2A	0.45	-	0	2345	28.1	30.6	34.6	38.0	39.2	4.9
2B	0.45	-	0	2343	-	-	37.8	-	-	-
3	0.35	BC	25	2357	31.0	37.2	43.1	44.3	48.1	5.4
4A	0.40	BC	25	2297	25.4	28.3	33.3	40.2	46.0	4.9
4B	0.40	BC	25	2350	-	-	37.4	-	-	-
5A	0.45	BC	25	2325	22.1	27.2	31.1	35.3	40.4	4.8
5B	0.45	BC	25	2335	-	-	33.9	-	-	-
6	0.35	BC	35	2339	26.6	32.8	37.7	43.1	46.0	4.8
7A	0.40	BC	35	2335	22.9	27.6	33.7	38.3	42.2	4.9
7B	0.40	BC	35	2338	-	-	35.4	-	-	-
8A	0.32	BC	58	2401	24.5	32.5	40.4	44.5	47.2	4.4
8B	0.32	BC	58	2409	-	-	39.6	-	-	-
9	0.35	PP	25	2397	38.1	41.9	47.2	-	53.2	6.7**
10	0.40	PP	25	2370	37.9	40.3	43.4	49.5	50.8	5.9
11	0.45	PP	25	2340	30.2	33.3	35.8	42.5	43.1	4.9
12	0.35	M	25	2375	30.9	34.9	41.5	46.6	47.7	6.3**
13	0.40	M	25	2361	27.4	33.3	37.5	45.0	49.4	5.4
14	0.45	M	25	2321	21.7	26.0	29.5	37.6	38.7	5.4

* Density of cylinders at one day

** Tested at 56 days

The flexural strength at 14 days of the concretes ranged from 4.4 to 5.9 Mpa (638 to 856 psi); the lowest strength being shown by the high-volume fly ash concrete, and the highest strength by the mixture incorporating 25 percent Pleasant Prairie fly ash and having a W/CM of 0.40. However, previously published data indicate that high-volume fly ash concrete will reach significantly higher flexural strength at later ages because of the pozzolanic reaction [8,11].

Table 3-4
Mechanical properties of the hardened concrete. (English units)

Mixture No.	W/CM	Fly Ash		Density,* lb/yd^3	Compressive Strength, psi					Flexural Strength at 14 d, psi
		Source	%		7 d	14 d	28 d	56 d	91 d	
1A	0.40	-	0	3973	4495	4698	5525	5684	6163	841
1B	0.40	-	0	4003	-	-	5046	-	-	-
2A	0.45	-	0	3952	4075	4437	5017	5510	5684	711
2B	0.45	-	0	3949	-	-	5481	-	-	-
3	0.35	BC	25	3973	4495	5394	6250	6424	6975	783
4A	0.40	BC	25	3872	3683	4104	4829	5829	6670	711
4B	0.40	BC	25	3961	-	-	5423	-	-	-
5A	0.45	BC	25	3919	3205	3944	4510	5119	5858	696
5B	0.45	BC	25	3936	-	-	4916	-	-	-
6	0.35	BC	35	3942	3857	4756	5467	6250	6670	696
7A	0.40	BC	35	3936	3321	4002	4887	5554	6119	711
7B	0.40	BC	35	3941	-	-	5133	-	-	-
8A	0.32	BC	58	4047	3553	4713	5858	6453	6844	638
8B	0.32	BC	58	4060	-	-	5742	-	-	-
9	0.35	PP	25	4040	5525	6076	6844	-	7714	972**
10	0.40	PP	25	3995	5496	5844	6293	7178	7366	856
11	0.45	PP	25	3944	4379	4829	5191	6163	6250	711
12	0.35	M	25	4003	4481	5061	6018	6757	6917	914**
13	0.40	M	25	3979	3973	4829	5438	6525	7163	783
14	0.45	M	25	3912	3147	3770	4278	5452	5612	783

* Density of cylinders at one day

** Tested at 56 days

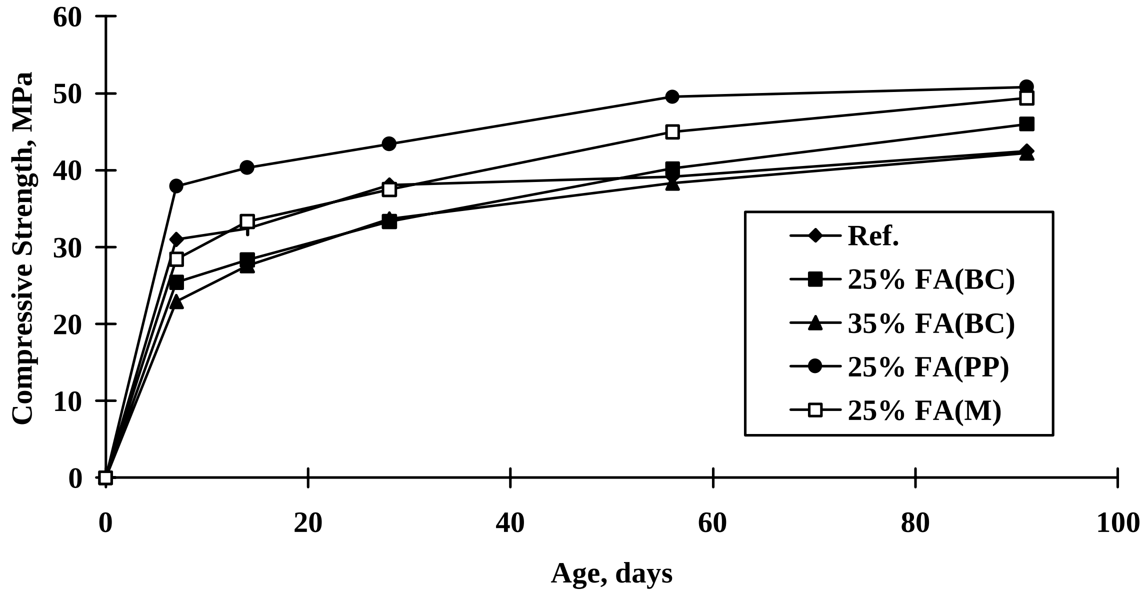

Figure 3-1
Compressive strength development of concrete made with a W/CM of 0.40.

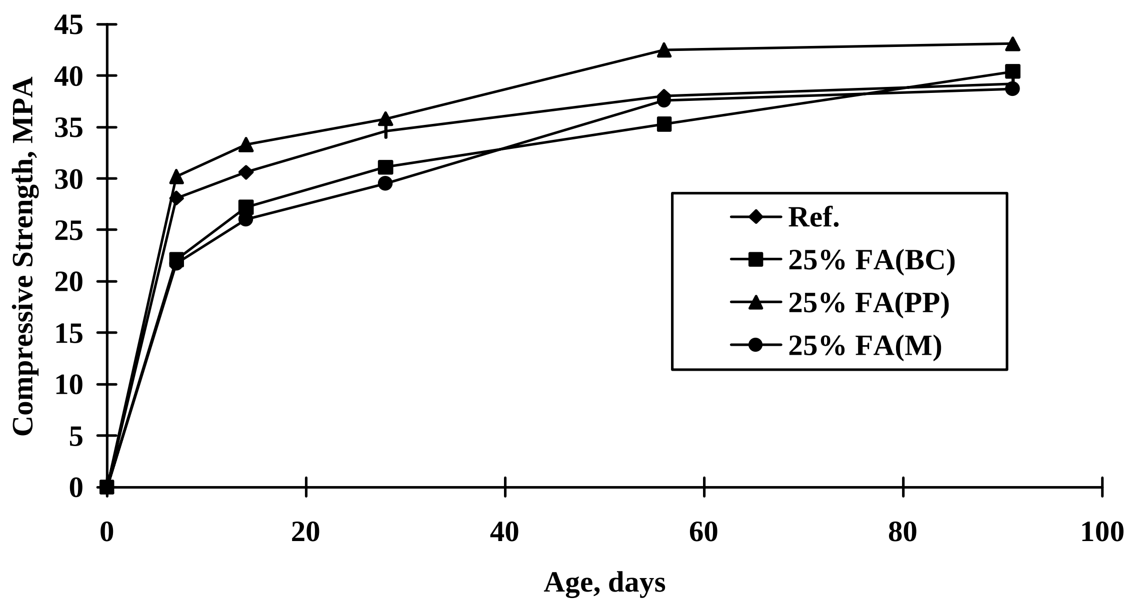

Figure 3-2
Compressive strength development of concrete made with a W/CM of 0.45

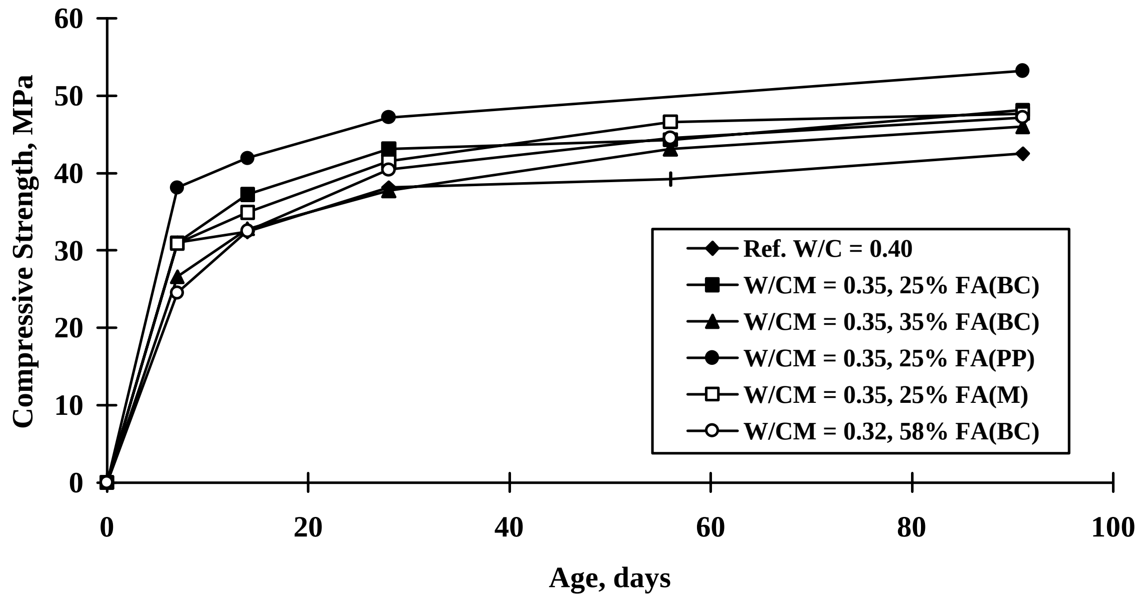

Figure 3-3
Compressive strength development of reference concrete made with a W/C of 0.40, and of fly ash concrete made with W/CM of 0.32 and 0.35.

Air-Void Parameters of the Hardened Concrete

The air-void parameters of the hardened concrete from the batch A of selected mixtures are given in Tables 3-5 and 3-6.

Table 3-5
Air-void parameters of the hardened concrete of selected mixtures. (SI units)

Mixture No.	W/CM	Fly Ash		Air Content, %	Specific Surface, mm^2/mm^3	Spacing Factor (˚) µm
		Source	%			
1A	0.40	-	0	3.8	40.3	138
2A	0.45	-	0	4.0	31.2	176
3	0.35	BC	25	4.1	27.1	113
4A	0.40	BC	25	6.2	42.7	106
5A	0.45	BC	25	5.0	34.2	142
7A	0.40	BC	35	5.5	36.1	132
8A	0.32	BC	58	4.4	26.9	179

The values of the spacing factor ranged from 106 to 179 µm (0.004 to 0.007 in.), and are below the upper limit of 230 µm (0.009 in.) set by the Canadian Standards Association (CSA A23.1-94) for adequate freezing and thawing durability

Table 3-6
Air-void parameters of the hardened concrete of selected mixtures. (English units)

Mixture No.	W/CM	Fly Ash		Air Content, %	Specific Surface, in^2/in^3	Spacing Factor (°) in.
		Source	%			
1A	0.40	-	0	3.8	1057	0.005
2A	0.45	-	0	4.0	818	0.007
3	0.35	BC	25	4.1	711	0.005
4A	0.40	BC	25	6.2	1120	0.004
5A	0.45	BC	25	5.0	897	0.006
7A	0.40	BC	35	5.5	947	0.005
8A	0.32	BC	58	4.4	705	0.007

De-Icing Salt Scaling Resistance

The resistance of concrete to the de-icing salt scaling is an important property of concrete for road slabs and bridge decks subject to the combined action of the freezing and thawing and de-icing salt. In general, air entrainment makes concrete more resistant to surface scaling caused by the de-icing salts. The strength of concrete, its W/C, cement content, and the use of supplementary cementing materials such as fly ash, slag, and silica fume also have significant effect on the scaling resistance. ACI 318 - Building Code specifies that concrete exposed to freezing and thawing in a moist condition or to de-icing chemicals shall have a minimum strength of 31 MPa (4500 psi), and meet the requirement of maximum water-to-cementitious materials ratio of 0.45. It also specifies that for concrete exposed to deicing chemicals, the combined weight of fly ash and other pozzolans conforming to ASTM C 618 shall not exceed 25% of the total weight of the cementitious materials. This specification is too conservative, and does not take into account the fact that there are instances where concrete containing up to 35% fly ash has performed satisfactorily in the ASTM de-icing salt scaling tests.

The results of this investigation on the de-icing salt scaling resistance of concrete are summarized in Tables 3-7 to 3-10, and the effect of several parameters on the de-icing salt scaling resistance of concrete is discussed below.

Table 3-7
Surface absorption, total amount of scaling residue, and final visual rating of the slabs of concrete made with Belews Creek fly ash. (SI units)

Mixture No.	W/CM	Fly Ash, %	Type of Surface	Moist Curing, days	Air Drying, days	Brand of CC*	Absorption after 6 hours, g/m^2	Scaling Residue kg/m^2	Final[(1)] Visual Rating
1A	0.40	0	Hor.	7	14	-	375	0.06	1.0
			Hor.	14	14	-	342	0.08	1.0
1B	0.40	0	Ver.	14	14	-	513	0.67	2.5
			Hor.	-	14	I	1068	0.02	1.0
			Hor.	-	14	II	831	0.05	1.0
			Hor.	-	14	III	1035	0.03	1.0
2A	0.45	0	Hor.	14	0	-	-	0.17	1.0
			Hor.	14	4	-	391	0.61	2.0
			Hor	14	14	-	546	1.27	3.5
2B	0.45	0	Ver.	14	14	-	564	1.28	3.5
			Hor.	-	14	I	1364	0.02	1.0
3	0.35	25	Hor.	7	14	-	391	0.63	3.5
			Hor.	14	14	-	375	0.46	3.0
4A	0.40	25	Hor.	7	14	-	571	0.76	2.0
			Hor.	14	14	-	619	0.66	2.5
			Hor.	28	14	-	554	2.31	3.5
4B	0.40	25	Ver.	14	14	-	512	3.28	4.5
			Hor.	-	14	I	1589	0.07	1.0
			Hor.	-	14	II	1394	0.10	1.5
			Hor.	-	14	III	1311	0.04	1.0
5A	0.45	25	Hor.	14	0	-	-	0.20	1.0
			Hor.	14	4	-	481	2.57	4.0
			Hor.	14	14	-	709	4.74	5.0
5B	0.45	25	Ver.	14	14	-	717	5.04	5.0
			Hor.	-	14	I	2225	0.07	2.0
6	0.35	35	Hor.	14	14	-	445	1.07	4.0
7A	0.40	35	Hor.	7	14	-	685	0.93	2.5
			Hor.	14	14	-	530	0.51	2.0
			Hor.	28	14	-	595	3.69	5.0
			Hor.	56	14	-	582	3.92	5.0
7B	0.40	35	Hor.	-	14	I	1972	0.05	2.0
			Hor.	-	14	II	1695	0.10	2.0
			Hor.	-	14	III	1964	0.14	1.5
			Ver.	-	14	I	1671	0.26	1.5
8A	0.32	58	Hor.	14	14	-	601	7.06	5.0
			Hor.	56	14	-	n.a.	5.63	5.0
			Ver.	14	14	-	600	7.71	5.0
8B	0.32	58	Hor.	-	14	I	n.a.	4.31	5.0
			Hor.	-	14	II	n.a.	4.25	5.0
			Hor.	-	14	III	n.a.	4.28	5.0

* CC: Curing compound

n.a.: data not available

(1): See Table 3-9 for description

Table 3-8
Surface absorption, total amount of scaling residue, and final visual rating of the slabs of concrete made with Belews Creek fly ash. (English units)

Mixture No.	W/CM	Fly Ash, %	Type of Surface	Moist Curing, days	Air Drying, days	Brand of CC*	Absorption after 6 hours, oz/ft²	Scaling Residue lb/ft²	Final[(1)] Visual Rating
1A	0.40	0	Hor.	7	14	-	1.2	0.012	1.0
			Hor.	14	14	-	1.1	0.016	1.0
1B	0.40	0	Ver.	14	14	-	1.7	0.137	2.5
			Hor.	-	14	I	3.5	0.004	1.0
			Hor.	-	14	II	2.7	0.010	1.0
			Hor.	-	14	III	3.4	0.006	1.0
2A	0.45	0	Hor.	14	0	-	-	0.035	1.0
			Hor.	14	4	-	1.3	0.125	2.0
			Hor	14	14	-	1.8	0.260	3.5
2B	0.45	0	Ver.	14	14	-	1.9	0.262	3.5
			Hor.	-	14	I	4.5	0.004	1.0
3	0.35	25	Hor.	7	14	-	1.3	0.129	3.5
			Hor.	14	14	-	1.2	0.094	3.0
4A	0.40	25	Hor.	7	14	-	1.9	0.156	2.0
			Hor.	14	14	-	2.0	0.135	2.5
			Hor.	28	14	-	1.8	0.473	3.5
4B	0.40	25	Ver.	14	14	-	1.7	0.672	4.5
			Hor.	-	14	I	5.2	0.014	1.0
			Hor.	-	14	II	4.6	0.021	1.5
			Hor.	-	14	III	4.3	0.008	1.0
5A	0.45	25	Hor.	14	0	-	-	0.041	1.0
			Hor.	14	4	-	1.6	0.526	4.0
			Hor.	14	14	-	2.3	0.971	5.0
5B	0.45	25	Ver.	14	14	-	2.4	1.032	5.0
			Hor.	-	14	I	7.3	0.014	2.0
6	0.35	35	Hor.	14	14	-	1.5	0.219	4.0
7A	0.40	35	Hor.	7	14	-	2.3	0.191	2.5
			Hor.	14	14	-	1.7	0.104	2.0
			Hor.	28	14	-	2.0	0.756	5.0
			Hor.	56	14	-	1.9	0.803	5.0
7B	0.40	35	Hor.	-	14	I	6.5	0.010	2.0
			Hor.	-	14	II	5.6	0.021	2.0
			Hor.	-	14	III	6.5	0.029	1.5
			Ver.	-	14	I	5.5	0.053	1.5
8A	0.32	58	Hor.	14	14	-	2.0	1.446	5.0
			Hor.	56	14	-	n.a.	1.153	5.0
			Ver.	14	14	-	2.0	1.579	5.0
8B	0.32	58	Hor.	-	14	I	n.a.	0.883	5.0
			Hor.	-	14	II	n.a.	0.870	5.0
			Hor.	-	14	III	n.a.	0.877	5.0

* CC: Curing compound

n.a.: data not available

(1): See Table 3-9 for description

Table 3-9
Surface absorption, total amount of scaling residue, and final visual rating of the slabs of concrete made with Pleasant Prairie and Montour fly ashes. (SI units)

Mixture No.	W/CM	Fly Ash,* %	Type of Surface	Moist Curing, days	Air Drying, days	Brand of CC**	Absorption after 6 hours, g/m^2	Scaling Residue, kg/m^2	Final[(1)] Visual Rating
9	0.35	25	Hor.	14	14	-	353	0.49	3.0
			Hor.	-	14	I	969	0.09	1.0
10	0.40	25	Hor.	14	14	-	517	4.21	5.0
			Hor.	14	28	-	739	5.20	5.0
11	0.45	25	Hor.	14	0	-	-	1.33	2.5
			Hor.	14	4	-	n.a.	2.88	4.0
			Hor.	14	14	-	714	5.56	5.0
12	0.35	25	Hor.	14	14	-	n.a.	5.53	5.0
			Hor.	-	14	I	n.a.	0.05	1.0
13	0.40	25	Hor.	14	14	-	637	5.20	5.0
			Hor.	28	14	-	640	5.45	5.0
14	0.45	25	Hor.	14	0	-	-	0.05	1.0
			Hor.	14	4	-	591	1.77	4.0
			Hor.	14	14	-	737	2.19	4.0

* Mixtures 9, 10 and 11 were made with Pleasant Prairie fly ash whereas mixtures 12, 13 and 14 were made with Montour fly ash.

** CC: Brand of curing compound

(1): From ASTM C 672 visual rating scale

Rating	Condition of surface
0	no scaling
1	very slight scaling (3.2 mm depth, max, no coarse aggregate visible)
2	slight to moderate scaling
3	moderate scaling (some coarse aggregate visible)
4	moderate to severe scaling
5	severe scaling (coarse aggregate visible over the entire surface)

Effect of the water-to-cementitious materials ratio

Figures 3-4 to 3-8 show the effect of water-to-cementitious materials ratio on the de-icing salt scaling resistance of the control portland cement and fly ash concretes tested after being conditioned in accordance with ASTM C 672; 14 days of moist curing followed by 14 days of air drying.

For the control portland cement concrete with a W/C of 0.40, the total mass of the scaling residue was negligible after 50 freezing and thawing cycles (Fig. 3-4). However, the total mass of the scaling residue for the control concrete with a W/C of 0.45 was 0.8 kg/m^2 (0.16 lb/ft^2) after only 15 cycles, and 1.3 kg/m^2 (1.27 lb/ft^2) after 50 cycles with a visual rating of 3.5, thus exceeding the limit of 0.8 kg/m^2 (0.16 lb/ft^2) specified by the Ontario Ministry of Transportation. ASTM C672 does not specify the determination of weight loss. Instead, it specifies a visual rating but no acceptance criterion. In general, a weight loss of 0.8 kg/m^2 (0.16 lb/ft^2) would correspond to a visual rating of about 2 to 3.

Table 3-10
Surface absorption, total amount of scaling residue, and final visual rating of the slabs of concrete made with Pleasant Prairie and Montour fly ashes. (English units)

Mixture No.	W/CM	Fly Ash,* %	Type of Surface	Moist Curing, days	Air Drying, days	Brand of CC**	Absorption after 6 hours, oz/ft^2	Scaling Residue, lb/ft^2	Final(1) Visual Rating
9	0.35	25	Hor.	14	14	-	1.2	0.100	3.0
			Hor.	-	14	I	3.2	0.018	1.0
10	0.40	25	Hor.	14	14	-	1.7	0.862	5.0
			Hor.	14	28	-	2.4	1.065	5.0
11	0.45	25	Hor.	14	0	-	-	0.272	2.5
			Hor.	14	4	-	n.a.	0.590	4.0
			Hor.	14	14	-	2.4	1.139	5.0
12	0.35	25	Hor.	14	14	-	n.a.	1.133	5.0
			Hor.	-	14	I	n.a.	0.010	1.0
13	0.40	25	Hor.	14	14	-	2.1	1.065	5.0
			Hor.	28	14	-	2.1	1.116	5.0
14	0.45	25	Hor.	14	0	-	-	0.010	1.0
			Hor.	14	4	-	2.0	0.363	4.0
			Hor.	14	14	-	2.4	0.449	4.0

* Mixtures 9, 10 and 11 were made with Pleasant Prairie fly ash whereas mixtures 12, 13 and 14 were made with Montour fly ash.

** CC: Brand of curing compound

(1): See Table 3-9 for description.

For concrete incorporating 25% Belews Creek fly ash (ASTM Class F fly ash produced with eastern bituminous coal) and with water-to-cementitious materials ratios of 0.35 and 0.40, the total mass of the scaling residues was less than 0.8 kg/m^2 (0.16 lb/ft^2) with visual ratings of 2.5 to 3; however, the concrete with a W/CM of 0.45 had severe scaling with the total mass of the scaling residue of 4.74 kg/m^2 (0.971 lb/ft^2) and a visual rating of 5 after 50 cycles of freezing and thawing (Fig. 3-5).

For concrete incorporating 25% Pleasant Prairie fly ash (ASTM Class C fly ash produced with western sub-bituminous coal from the Powder River Basin) and with a W/CM of 0.35, the total mass of the scaling residues was less than 0.8 kg/m^2 (0.16 lb/ft^2) after 50 freezing and thawing cycles; however, the concrete with water-to-cementitious materials ratios of 0.40 and 0.45 had severe scaling and the total mass of the scaling residue was 4.21 and 5.56 kg/m^2, (0.862 and 1.139 lb/ft^2)respectively, with a visual rating of 5 for both (Fig. 3-6). Most of the scaling occurred within the first 10 to 15 cycles for these two concretes, and the rate of the scaling decreased when most of the mortar had been lost and the coarse aggregate had been exposed.

For concrete incorporating 25% Montour fly ash (ASTM Class F fly ash produced with central Pennsylvania bituminous coal), the concrete had severe scaling regardless of the W/CM (Fig. 3-7).

The poor performance of Montour fly ash in the de-icing salt scaling test is probably due to its relatively coarse particle size, higher loss on ignition and poor pozzolanic activity. The total mass of the scaling residue decreased with an increase in the W/CM.

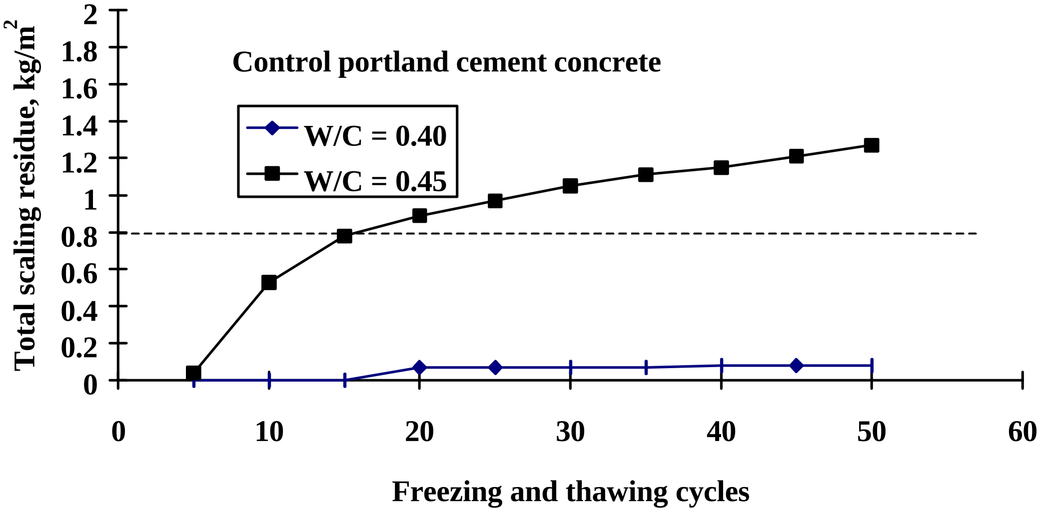

Figure 3-4
Effect of W/C on the resistance of the control portland cement concrete to the de-icing salt scaling.

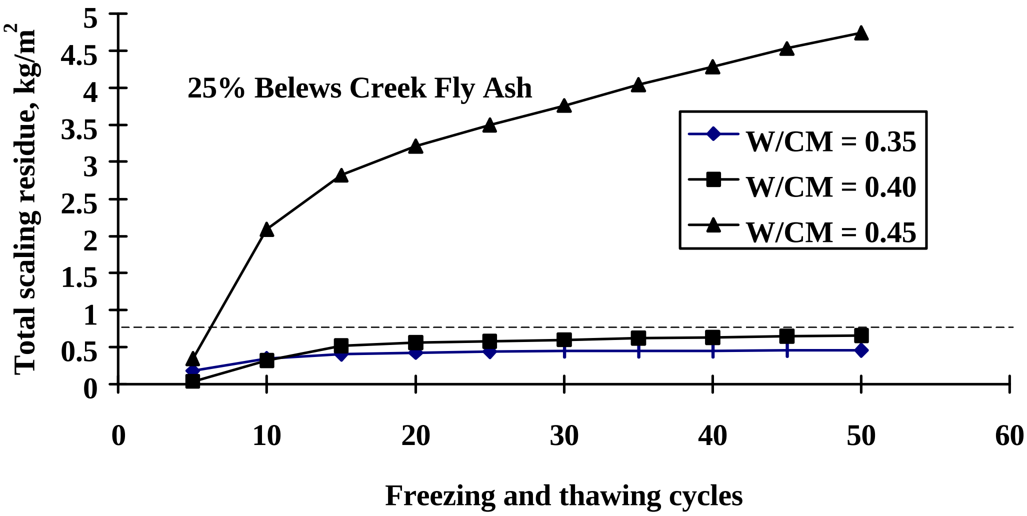

Figure 3-5
Effect of W/CM on the resistance of the concrete incorporating 25% Belews Creek (ASTM Class F) fly ash to the de-icing salt scaling.

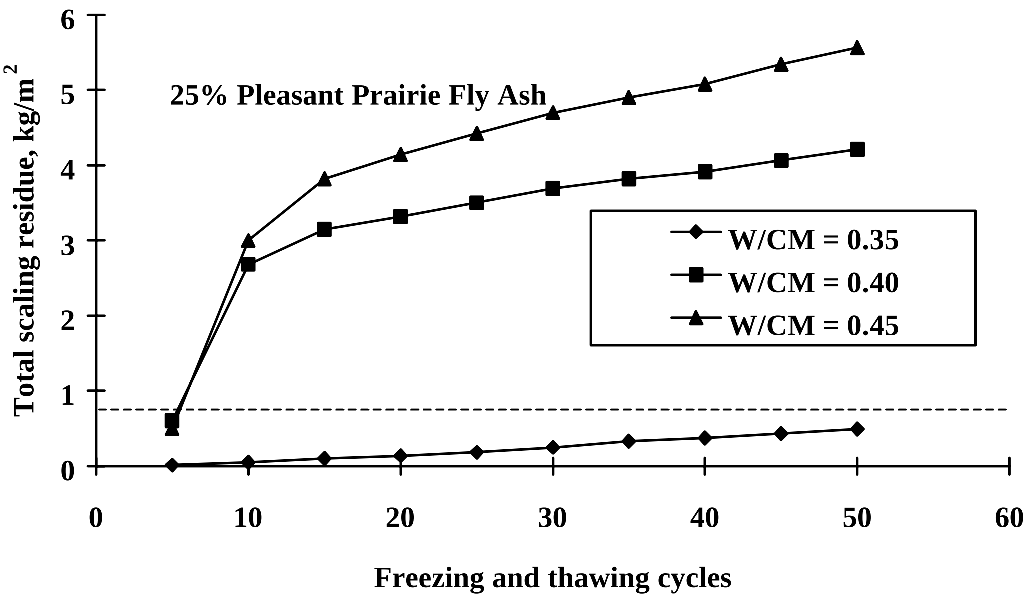

Figure 3-6
Effect of the W/CM on the resistance of the concrete incorporating 25% Pleasant Prairie (ASTM Class C) fly ash to the de-icing salt scaling.

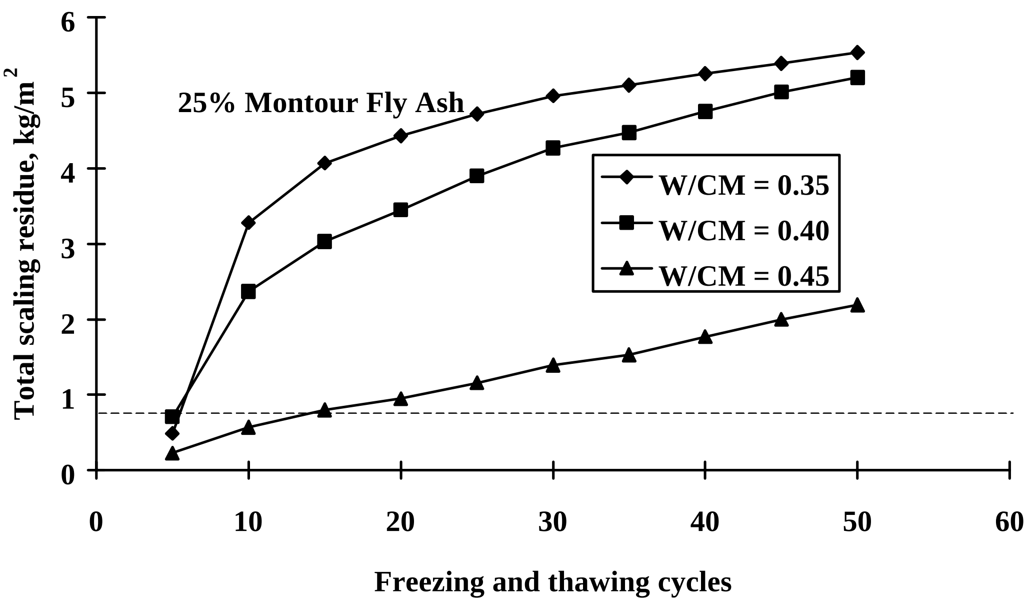

Figure 3-7
Effect of W/CM on the resistance of the concrete incorporating 25% Montour (ASTM Class F) fly ash to the de-icing salt scaling.

For concrete incorporating 35% Belews Creek fly ash and with a W/CM of 0.40, the total mass of the scaling residues was less than 0.8 kg/m^2 (0.16 lb/ft^2)with a visual rating of 2; whereas for that with a W/CM of 0.35, the total mass of the scaling residue was 1.07 kg/m^2 (0.219 lb/ft^2) with a visual rating of 4 after 50 cycles (Fig. 3-8). As was the case with 25% Montour ash (Fig. 3-7), the total mass of the scaling residue for concrete with 35% Belews Creek fly ash decreased with an increase in the W/CM. This is unexplained and additional mixtures will be made to confirm and explain this phenomenon. However, it should be mentioned that similar results have been reported by others for normal portland cement concrete subject to de-icing salt scaling in the presence of a proprietary salt [12].

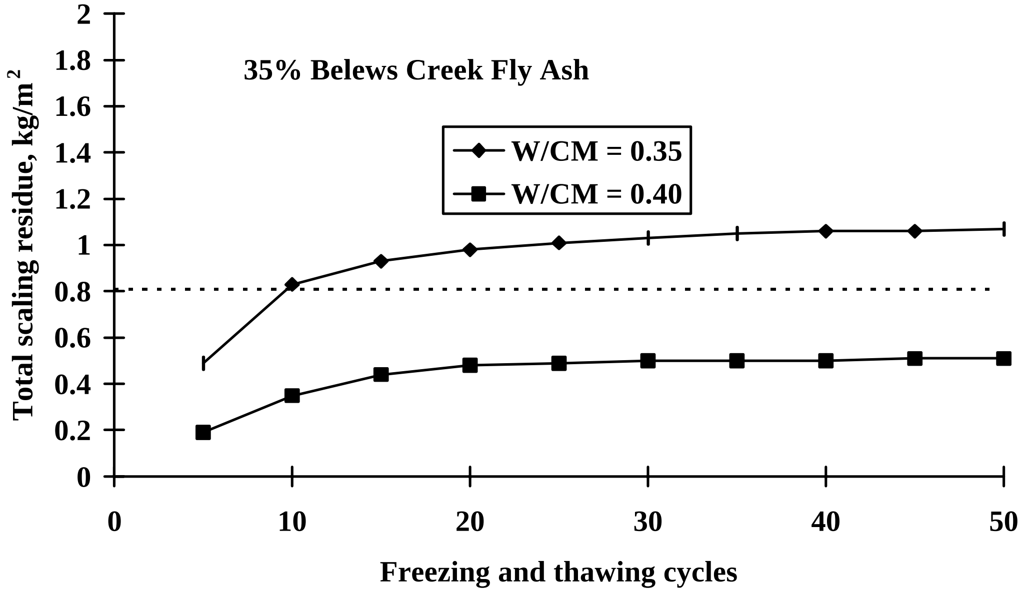

Figure 3-8
Effect of W/CM on the resistance of the concrete incorporating 35% Belews Creek (ASTM Class F) fly ash to the de-icing salt scaling.

From the above results, it is apparent that W/CM has significant effect on the resistance of the concrete to the de-icing salt scaling. Even for the control concrete without fly ash, it seems that the W/C should be ≤0.40 for satisfactory scaling resistance. However, for some fly ash concretes, even lower W/CM does not guarantee a good performance in the de-icing salt scaling test. The results indicated that the type and the amount of fly ash used also have significant effect on the scaling resistance, and these are discussed below.

Figure 3-9 illustrates the effect of the W/CM on the water absorption by the surface of the slabs. It shows that, as expected, the absorption increased significantly with the W/CM of the concrete.

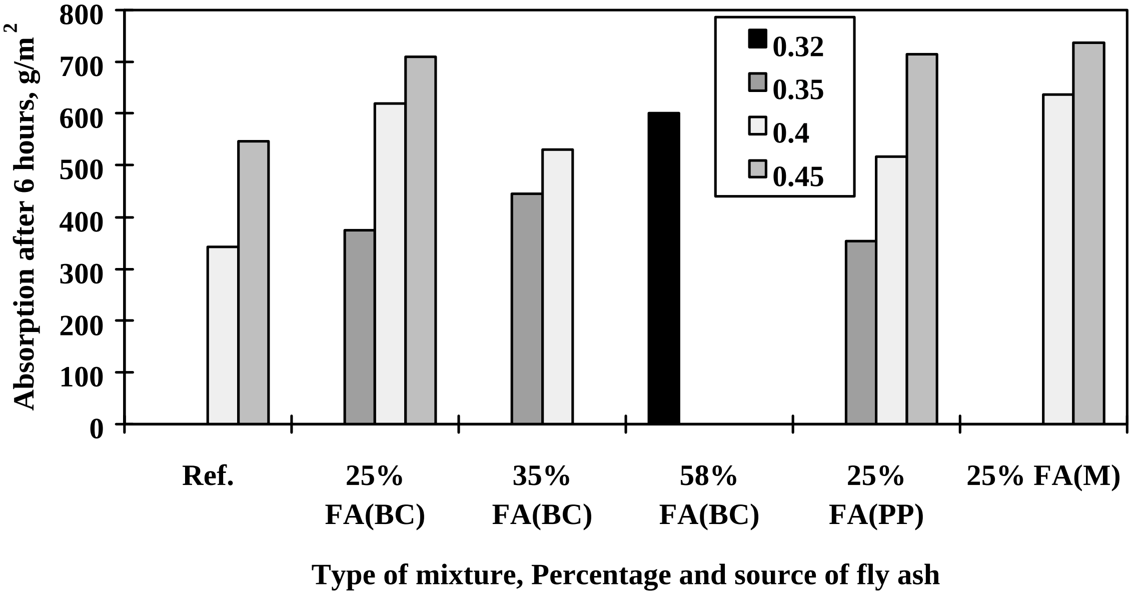

Figure 3-9
Effect of W/CM, source of fly ash, and percentage of fly ash on the water absorption of the surface of the concrete slabs.

Effect of the amount of Belews Creek fly ash in concrete

Figures 3-10 to 3-12 show the effect of the amount of the Belews Creek fly ash (ASTM Class F fly ash produced with eastern bituminous coal) in concrete on the resistance to the de-icing salt scaling. Again the test were performed on slabs conditioned in accordance with ASTM C 672.

The total mass of the scaling residue for control concrete and concretes incorporating 25 or 35% fly ash and with a W/CM of 0.40 was below the limit of 0.8 kg/m^2 (0.16 lb/ft^2) (as specified by the Ontario Ministry of Transportation) after 50 cycles of freezing and thawing. The concrete incorporating 25% fly ash showed slightly more scaling than the concrete incorporating 35% fly ash. This is probably due to the nature of the test, and the large variations which are associated with this.

The concrete incorporating 25% fly ash with a W/CM of 0.45 showed significantly more scaling than the reference concrete (Fig. 3-11).

For the fly ash concrete with W/CM ≤0.35, the scaling increased with an increase in the amount of fly ash used. At the fly ash content of 58% (high-volume fly ash concrete), the concrete had a total mass of the scaling residue of 7.06 kg/m^2 (1.446 lb/ft^2) after 50 cycles of freezing and thawing (Fig. 3-12). The poor performance of the high-volume fly ash concrete in the scaling test was in line with previously published data by CANMET [8,9].

The effect of the amount of fly ash on the water absorption of the slabs is not clear (Fig. 3-9).

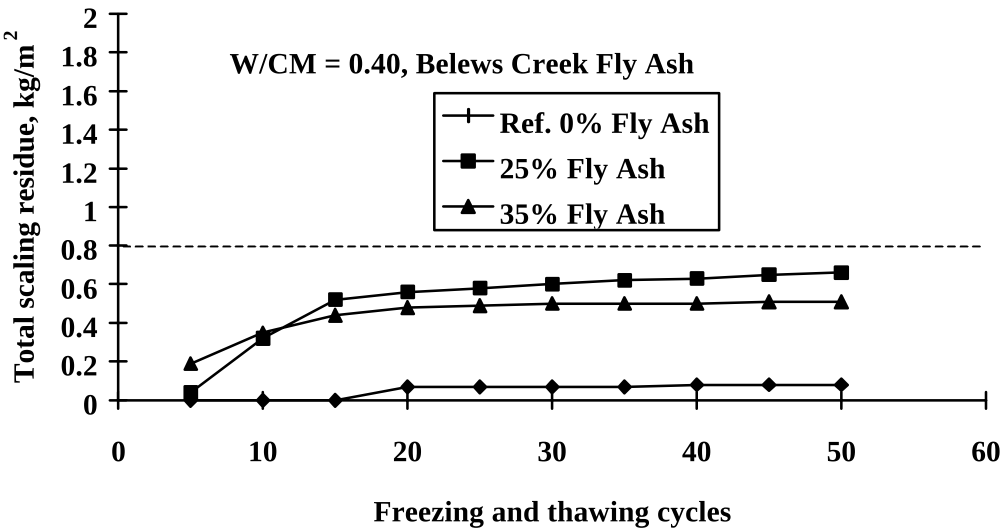

Figure 3-10
Effect of the fly ash content on the de-icing salt scaling resistance of the concrete with W/CM of 0.40 and made with Belews Creek fly ash.

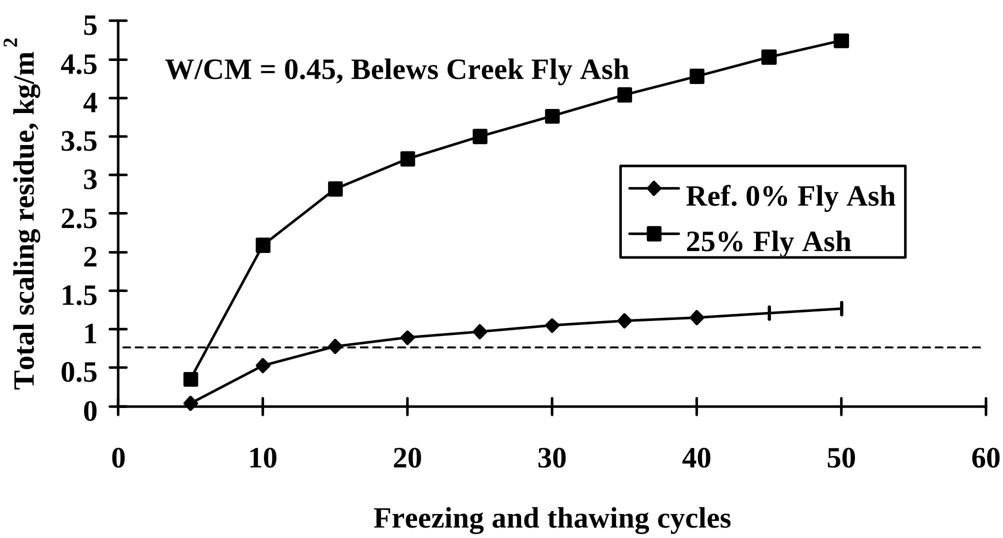

Figure 3-11
Effect of the fly ash content on the de-icing salt scaling resistance of the concrete with W/CM of 0.45 and made with Belews Creek fly ash.

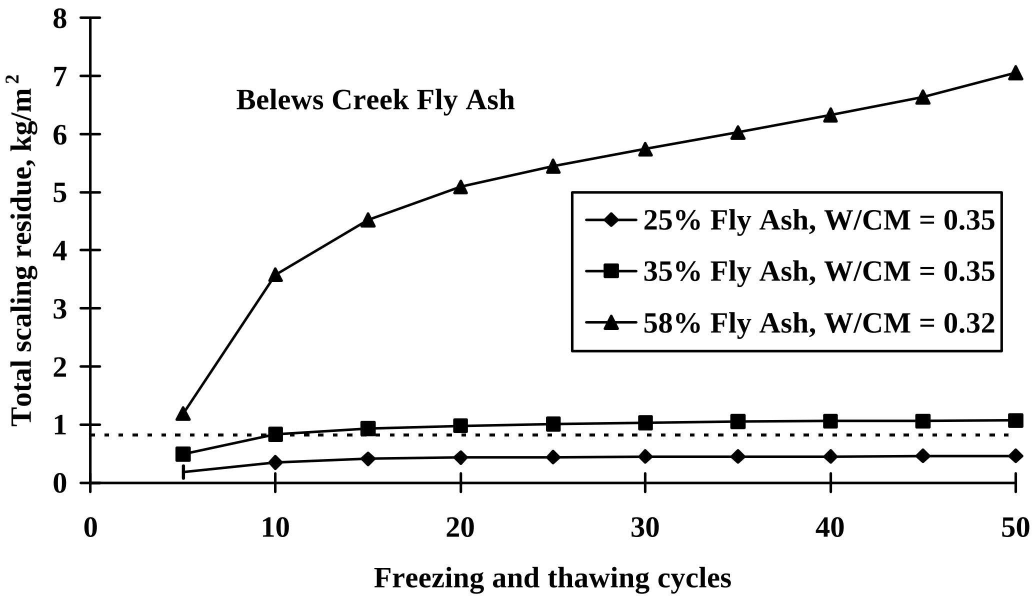

Figure 3-12
Effect of the fly ash content on the de-icing salt scaling resistance of the concrete with W/CM≤0.35, and made with Belews Creek fly ash.

Effect of the fly ash type

The chemical and mineralogical composition and fineness of fly ashes vary and these depend on the type of coal used and the operating conditions in the thermal power stations. Thus, the reactivity of the fly ash, and consequently the microstructure of the binder at the on-set of the freezing and thawing in the presence of de-icing salt may be very different.

Figures 3-13 to 3-15 show the total mass of the scaling residue as a function of the freezing and thawing cycling for concretes incorporating different fly ashes and with the water-to-cementitious materials ratios ranging from 0.35 to 0.45. The percentage of the fly ash used was kept constant at 25% by weight of the total cementitious materials. Once again, the tests were performed on slabs conditioned in accordance with ASTM C 672.

At a W/CM of 0.35, the concrete incorporating the fly ash produced with the eastern bituminous coal (Belews Creek) or the fly ash produced with the western sub-bituminous coal from the Powder River Basin (Pleasant Prairie) had good resistance to the freezing and thawing cycling in the presence of the de-icing salt. The concrete made with the fly ash produced with the central Pensylvania coal (Montour), however, showed severe scaling even after 10 to 15 cycles (Fig. 3-13).

At a W/CM of 0.40, the concrete with Belews Creek fly ash performed well and the scaling mass was 0.67 kg/m^2 (0.137 lb/ft^2) after 50 cycles of freezing and thawing with a visual rating of 2.5;

the concretes with Pleasant Prairie or Montour fly ashes showed severe scaling with a visual rating of 5 after 50 cycles (Fig. 3-14).

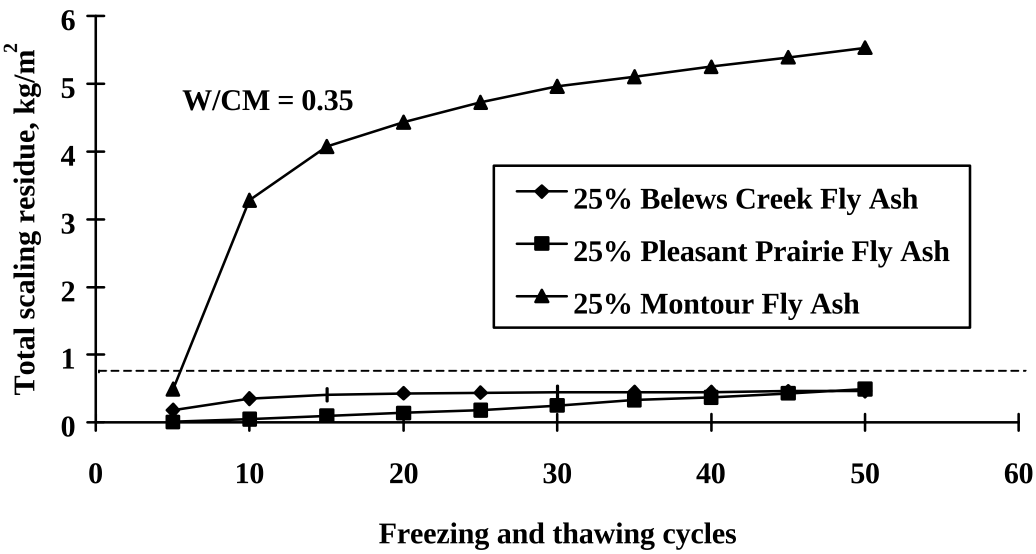

Figure 3-13
Effect of the type of fly ash used on the de-icing salt scaling resistance of the concrete with W/CM of 0.35.

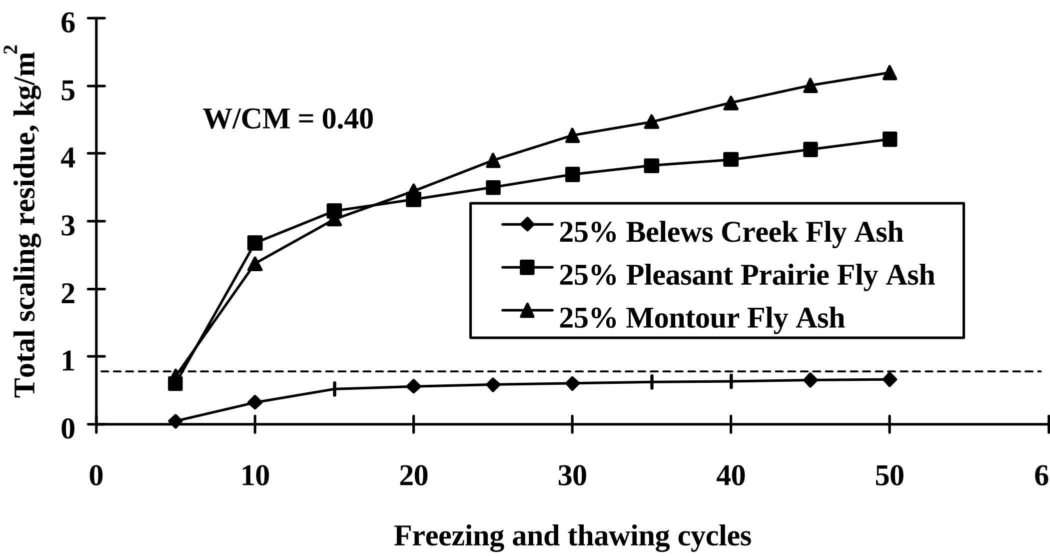

Figure 3-14
Effect of the type of fly ash used on the de-icing salt scaling resistance of the concrete with W/CM of 0.40.

All the three concretes with a W/CM of 0.45 and incorporating different types of fly ashes had severe scaling with visual ratings of 4 for the concrete with Montour fly ash and 5 for the concrete with Belews Creek or Pleasant Prairie fly ash (Fig. 3-15).

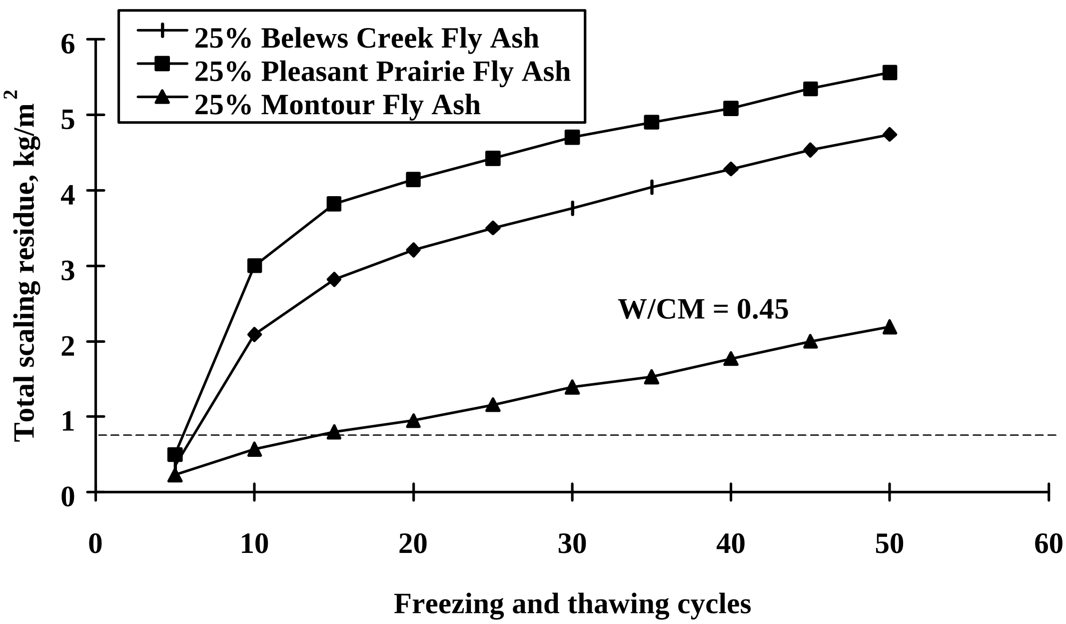

Figure 3-15
Effect of the type of fly ash used on the de-icing salt scaling resistance of the concrete with W/CM of 0.45.

The above results indicate that the type of the fly ash used would have significant effect on the de-icing salt scaling resistance of concrete.

There is no significant effect of the type of fly ash on the water absorption of the slabs; the different fly ash concretes showed, in general, very similar absorption values (Fig. 3-9).

Effect of the Duration of Moist Curing

The effect of the duration of the moist curing period on the scaling resistance is not totally clear as illustrated in Fig. 3-16. For the reference concrete, increasing the moist-curing period from 7 to 14 days had virtually no influence on the scaling resistance of the concrete, the amount of scaling residue being very low in both cases. For the fly ash mixtures, increasing the moist-curing period from 7 to 14 days decreased slightly the amount of the scaling residue, and this would be expected as the extended moist curing improves the quality of concrete because of the pozzolanic properties of the fly ash. When the moist curing period was extended to 28 days, and 56 days in the case of mixture incorporating 35% fly ash, the amount of the scaling residue increased significantly. It appears from these results that long curing periods have a detrimental effect on the scaling resistance of the fly ash concrete. For the high-volume fly ash concrete, increasing the moist-curing period from 14 to 56 days improved noticeably the scaling resistance of the concrete although the amount of scaling residue was still very high. Other investigations have shown that extended curing periods do not improve significantly the scaling resistance of fly ash concrete [6,13].

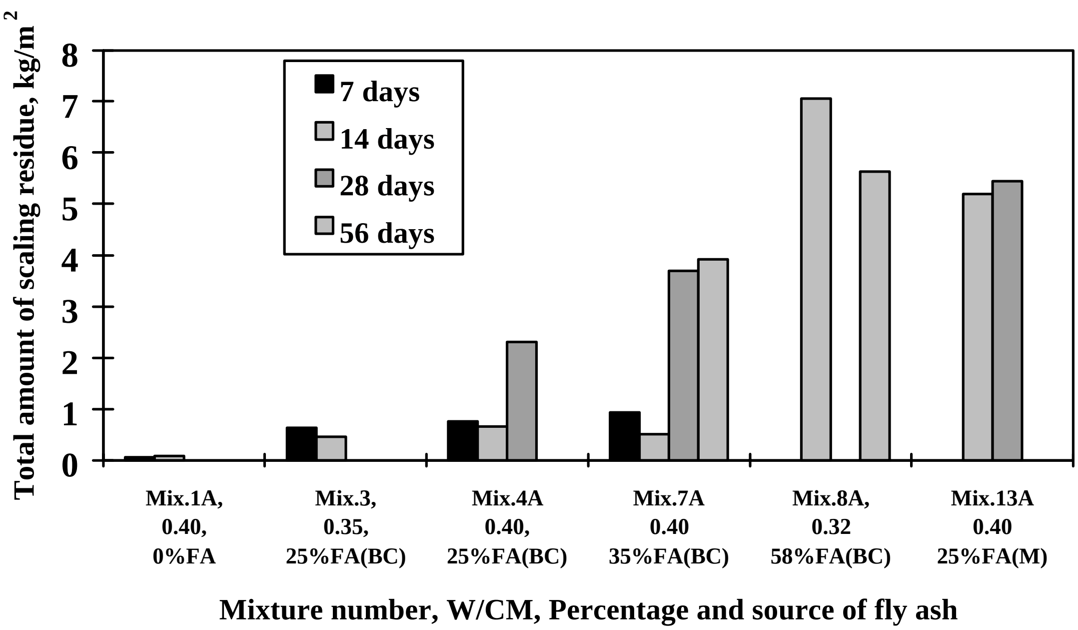

Figure 3-16
Effect of the duration of the moist curing on the total amount of scaling residue.

The effect of the duration of curing on the water absorption by the surface of the slabs is illustrated in Fig. 3-17; the fly ash concretes had noticeably higher absorption than the reference concrete of the same water-to-cementitious materials ratio. This indicates that the surface of the fly ash concrete was more porous than that of the reference concrete; this is also true for fly ash concrete moist-cured for 28 or 56 days compared to the reference concrete moist-cured for only 7 days, and despite the fact that the compressive strength of the fly ash concrete was higher than that of the reference concrete at these ages. The extended moist-curing period, as also illustrated in Fig. 3-17 did not clearly reduce the absorption by the surface of the slabs, and this was unexpected given the greater maturity of the concrete. However, the absorption was determined on concrete that had been subjected to drying. This probably altered the pore structure and caused some microcracking at the surface of the slabs, and the absorption was possibly a function of both the porosity of the matrix and the amount of microcracking at the surface of the concrete. The effect of the drying on the surface of the slabs including the development of microcracking was probably a function of the concrete composition and its maturity (duration of moist curing), and it is possible that this effect was more severe for the fly ash concrete, and was even more pronounced when extended moist-curing periods were used.

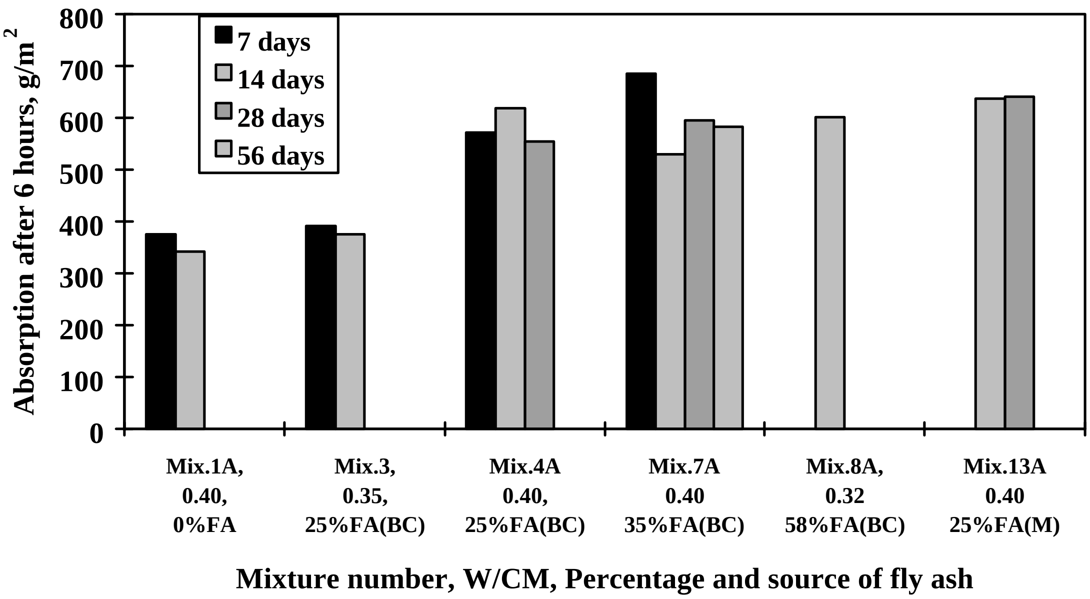

Figure 3-17
Effect of the duration of the moist curing on the water absorption of the surface of the concrete slabs.

The scaling resistance is also probably related to both the porosity of the matrix and the amount of microcracking at the surface of the concrete. However, the relation between the absorption and the scaling resistance is not clear as illustrated in Figures 3-16 and 3-17; some slabs show similar absorption values but perform very differently in the scaling test. This indicates that the relative influence of the porosity of the matrix and of the microcracking is not the same for the absorption and the scaling resistance of the concrete. Also, these two parameters depend on several other factors; for example, the scaling resistance is probably affected by the tensile strength and the quality of the air-void parameters at the surface of the concrete.

Effect of the Duration of Air Drying

The effect of the duration of air-drying on the scaling resistance of the concrete is illustrated in Figure 3-18. The results show that the amount of scaling residue increased significantly with an increase in the drying period. Mixtures 2, 5 and 14 performed excellently in the scaling test when the slabs were not subjected to any drying period whereas they failed to meet the specified limits for the mass of scaling residue when tested using the standard curing regime. Similarly, mixture 11 performed significantly better when the duration of drying was reduced although it failed to meet the specified limit even without any drying period. The data confirm that the drying affects significantly the surface of the concrete slabs and make it more vulnerable to scaling, probably through the alteration of the pore structure and development of microcracking.

The effect of the duration of air-drying on the water absorption of the concrete surface is illustrated in Fig. 3-19, and as expected, the absorption increased with the duration of drying.

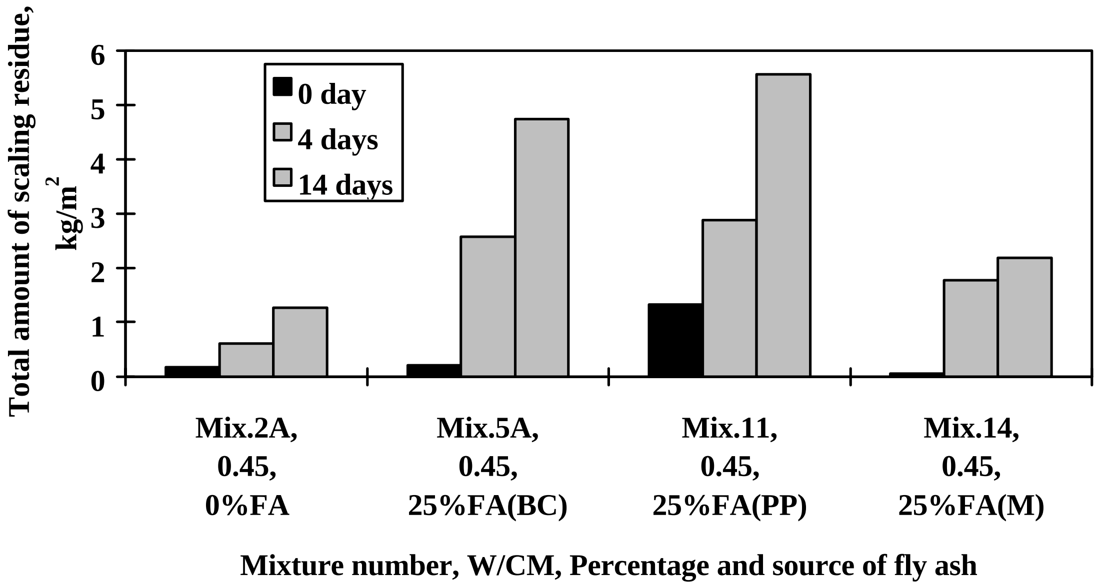

Figure 3-18
Effect of the duration of the air drying on the total amount of scaling residue.

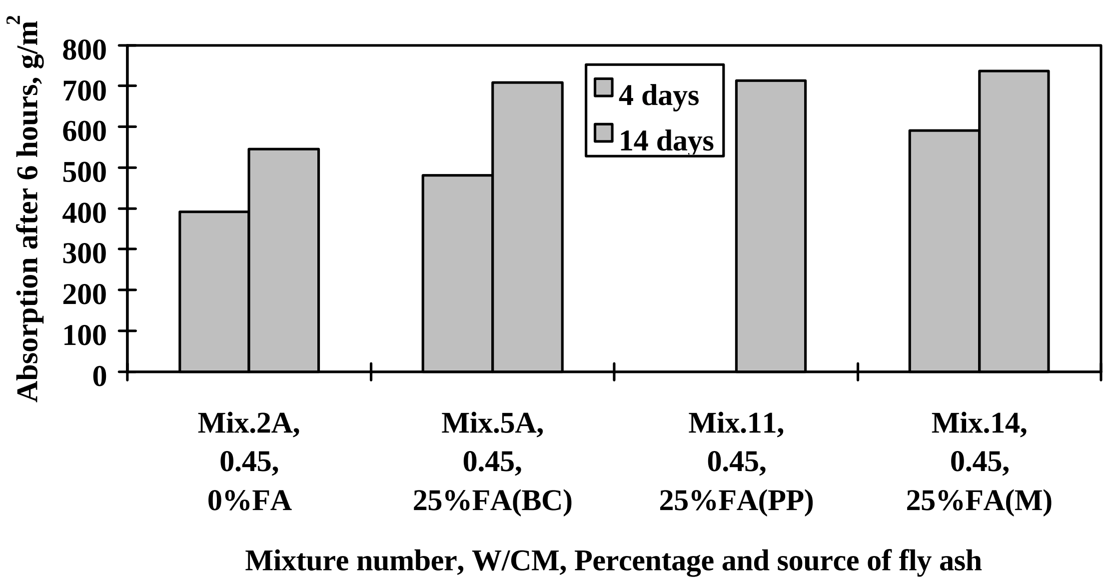

Figure 3-19
Effect of the duration of the air drying on the water absorption of the surface of the concrete slabs.

Performance of Surfaces Cast Vertically versus those Cast Horizontally

These tests were carried out in order to confirm if the scaling of the concrete was due largely to a weak surface layer that is formed during the casting and finishing of the horizontal slabs. By casting the slabs vertically, the effect of the surface finishing was avoided.

The scaling resistance of slabs from the same mixtures cast horizontally and vertically is illustrated in Figure 3-20. The vertically cast slabs from mixtures 1 and 4 showed noticeably more scaling than the horizontally cast slabs, however, both types of slabs from mixtures 2, 5 and 8 showed similar amounts of the scaling residue. The finishing of the horizontally cast slabs did not make them more vulnerable to scaling than the vertically cast slabs. In fact, two slabs cast horizontally performed better than the slabs cast vertically, possibly due to the variability in the test. This indicate that the finishing of the slabs was not a determinant factor for explaining the lower performance of fly ash concrete in the de-icing salt scaling test.

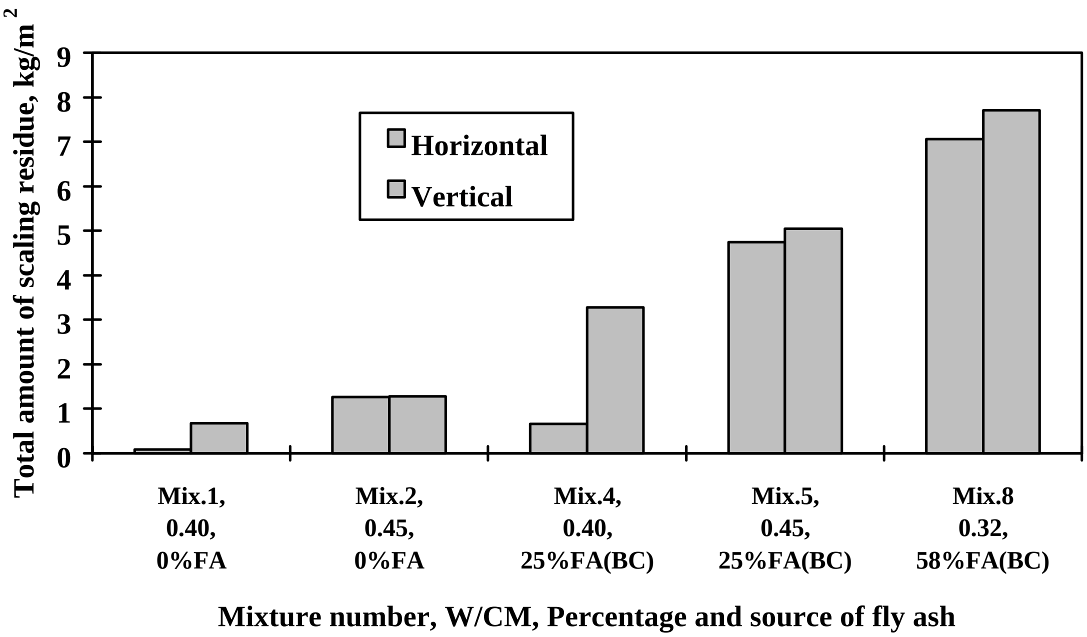

Figure 3-20
Effect of vertical versus horizontal casting on the total amount of scaling residue.

The water absorption of the vertically and the horizontally cast slabs is shown in Figure 3-21. In general, both slabs from the same mixture had similar absorption values, the exception being the vertically cast slabs from mixture 1 which showed noticeably more absorption than the horizontally cast slabs.

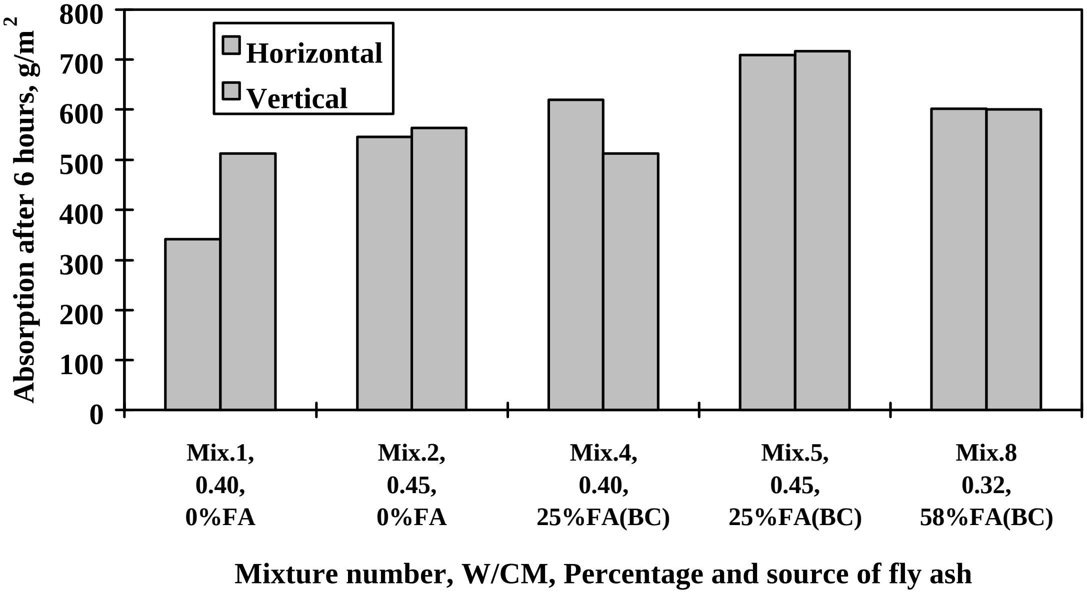

Figure 3-21
Effect of vertical versus horizontal casting on the water absorption of the surface of the concrete slabs.

Performance of Concrete Treated with Curing Compound

The characteristics of concrete surface layers are affected by the method of curing, and this influences the resistance of the concrete to the de-icing salt scaling. As in North America most of concrete road slabs and bridge decks are now cured with curing compounds instead of with wet burlap; it is, therefore, important to determine the effect of the type of curing on the de-icing salt scaling resistance of concrete. For concrete cured with wet burlap, external water can penetrate into the concrete at early ages to facilitate the hydration; whereas for concrete with properly applied curing compounds, the loss of water from the surface of the concrete is prevented and generally no external water can get into the concrete.

Figure 3-22 illustrates the total amount of the scaling residue of the moist-cured slabs and of the slabs from the same mixture that were cured using three different curing compounds. The use of the curing compounds improved significantly the scaling resistance of all the concretes tested. The effect was especially significant for fly ash concrete mixtures 2, 5 and 12 for which the amount of the scaling residue was over the specified limit when moist-cured, but was almost negligible when cured using a curing compound. The performance of the high-volume fly ash concrete in the scaling test was improved significantly by the use of the curing compounds but the amounts of the scaling residue were still high at about 4.3 kg/m^2 (0.88 lb/ft^2). There was practically no difference in the performance of the three different curing compounds used in this study. The use of curing compound appears to be a possible solution for making fly ash concrete more durable to freezing and thawing in the presence of de-icing salts. However, the curing compound might not be effective enough to prevent severe scaling for concretes that have shown very poor performance in the standard scaling test. These results on the excellent performance of concrete treated with curing compound confirm the data published by others [3,4,13,14].

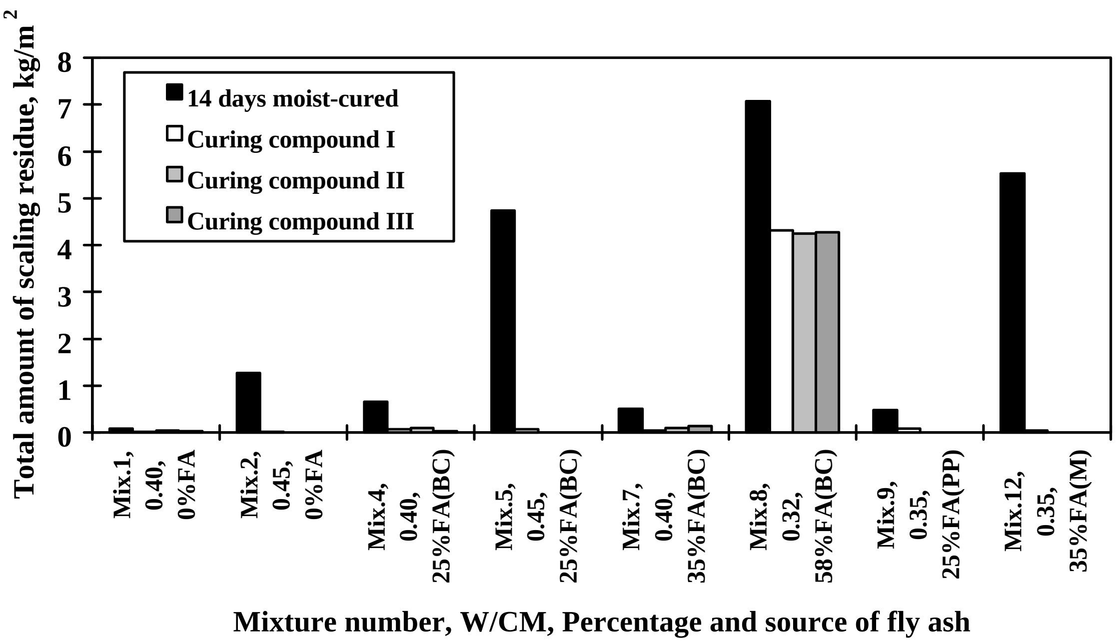

Figure 3-22
Effect of the curing compound on the total amount of scaling residue.

The absorption of the moist-cured slabs and of the slabs cured using the curing compounds is illustrated in Figure 3-23. The slabs treated with curing compound showed much more absorption than the moist-cured slabs. Notwithstanding the above, the slabs treated with curing compound showed superior performance in the de-icing salt scaling test compared with those cured in the moist-curing room.

The curing compound did not totally prevent the surface of the concrete slab to dry during the curing period, and in addition, no external water penetrated into the concrete as opposed to the moist-cured specimens. When the absorption test was performed, the slabs cured with the curing compound were probably in a dryer state than the moist-cured slabs, and this explains the higher absorption values measured on the former slabs. The superior performance of the slabs cured with the curing compound may be explained in terms of lower degree of microcracking.

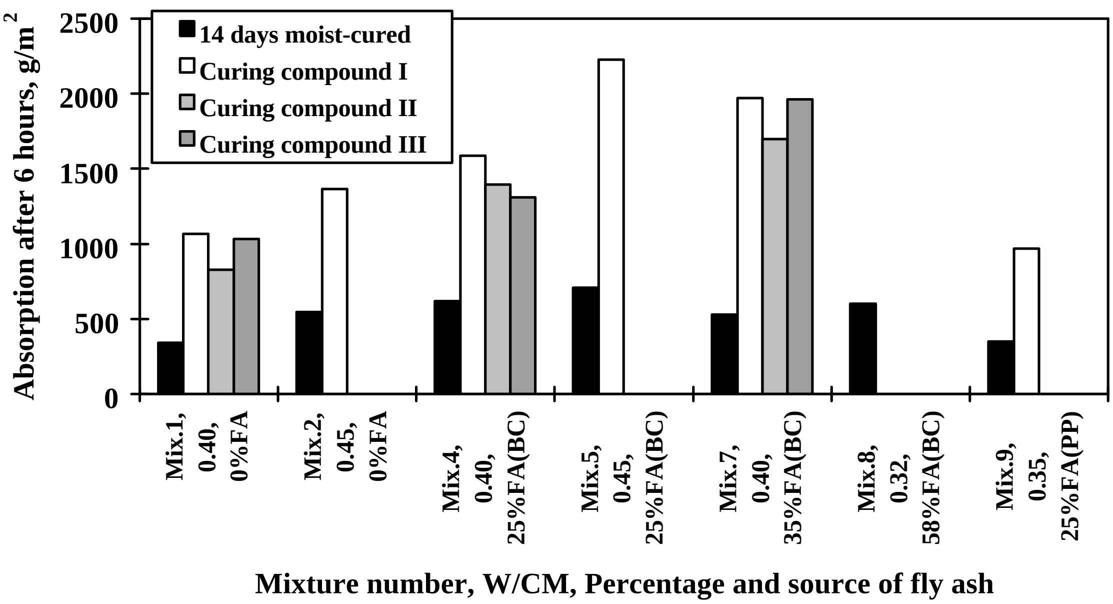

Figure 3-23
Effect of the curing compounds on the water absorption of the surface of the concrete slabs.

General Discussion

As expected, the above results demonstrated that several parameters, and most probably a combination of those parameters, determine whether the concrete will be resistant to de-icing salt scaling or not. First, the results confirm that the W/CM of the concrete has a strong influence on its scaling resistance. In general, it appears that the W/CM of the concrete should be 0.40 or less to make it resistant to de-icing salt scaling. However, these low W/CM do not guarantee that the concrete will have a good scaling resistance.

The incorporation of fly ash as partial replacement for cement tends to reduce the scaling resistance of the concrete. However, the results also showed that concrete incorporating up to 35% fly ash could perform satisfactorily in the scaling test but, this result was obtained with the ASTM Class F fly ash produced with eastern bituminous coal (Belews Creek) only; each fly ash is unique.

It appears that extended moist-curing periods, i.e. more than 14 days fail to improve the scaling resistance of the concrete; on the contrary, the extended moist-curing periods can be detrimental. It is a well known fact that extended moist-curing periods improve the quality of plain concrete and concrete incorporating fly ash. However, the above does not appear to hold true when concrete is subjected to the de-icing salt scaling test.

Extended drying periods increase the amount of scaling significantly, and the effect is much more significant for the fly ash concrete than for the reference concrete. It appears that for the concretes investigated, if there was no drying, de-icing salts scaling would almost not be a problem.

In the field after the curing has been done in accordance with the specifications (this rarely happens in practice), there is no control on the actual duration of moist-curing and drying that the concrete will be subjected to before it is going to be exposed to freezing and thawing and de-icing salts. Most probably, the concrete will be subjected to a number of wetting periods during which hydration will continue; also it may experience extended drying periods that, according to the above test results, would make the concrete more susceptible to scaling. How this wetting and drying cycling will affect the scaling resistance of concrete is unknown at this stage.

The use of curing compound instead of moist-curing improved considerably the scaling resistance of the concrete. It appears that curing compound may be a means to make concrete resistant to de-icing salts scaling that otherwise would fail in the standard scaling test. However, the results have demonstrated that the use of curing compound could not be the solution for concretes that perform very poorly in the standard test even though the amount of scaling is reduced significantly. Although the use of curing compound improved significantly the scaling resistance of concrete in the laboratory, its performance in the field is unknown. Eventually, the curing compound in the field would be removed from the surface of the concrete under the action of the sun and traffic, and instead of the 14 days of air drying used in the laboratory test, the concrete in the field will be exposed to the wetting and drying cycling mentioned above before being exposed to the de-icing salts. Again, how this will affect the performance of concrete is unknown.

In general, it appears that it is during the drying period that the surface of the moist-cured concrete is greatly affected and becomes susceptible to serious scaling due to the alterations in the pore structure and to the development of microcracking. It is possible that the drying has more effect on the fly ash concrete than on the normal portland cement concrete, and this could explain the lower performance of the former concrete in the scaling test. A possible explanation for this could be that the numerous unreacted fly ash particles at early ages are acting as very small aggregates in the paste, and thus are providing some restraint to shrinkage when the paste is drying resulting in induced stresses and microcracks. More research is needed in this area.

The drying does not seem to affect to the same extent the concrete that was cured using a curing compound, especially fly ash concretes. It is possible that some drying occurred in the slabs during the period the curing-compound treated slabs were cured. Consequently, the shock experienced by these slabs when exposed to drying was probably less severe than for the moist-cured slabs, thus reducing the amount of microcracking. Once again, additional investigations are needed in this area.

4

MICROSTRUCTURE OF THE CEMENT PASTE INCORPORATING FLY ASH AND THE DE-ICING SALT SCALING OF THE FLY ASH CONCRETE

Fly ash is a fine-grained material consisting mostly of spherical, glassy particles. When ASTM Class F fly ash is incorporated in mortar or concrete, the fly ash particles react with $Ca(OH)_2$ generated from the portland cement hydration to form compounds possessing cementitious properties. The ASTM Class C fly ash, which is mainly composed of glass phase and some crystalline phases such as C_2S, C_3A, and $CaSO_4$, has self hardening properties when mixed with water in addition to the pozzolanic properties like that of Class F ash.

There is generally a transition zone between the fly ash particles and the surrounding reaction products in portland cement paste incorporating fly ash [15,16]. Figure 4-1 shows a schematic model of fly ash in concrete. The transition zone is usually more porous than the fly ash particles and the surrounding reaction products, and the thickness of this zone will generally decrease whereas the density will increase with the progress of the pozzolanic reaction of the fly ash.

Figures 4-2 and 4-3 show backscattered electron images (BEI) from a cement paste incorporating 56% ASTM Class F fly ash cured for 28 days and 180 days, respectively. At 28 days, there appears to be a porous zone around some fly ash particles, manifested as black rings around the particles in the BEI. By 180 days, significant densification has taken place, although residual, typically spherical fly ash particles remain in the system. Compared with that at 28 days, microstructure of the paste is more unified and the hydration and reaction products in general are more evenly distributed in the system. The porous transition zone around the fly ash particles appears to have densified substantially, although some regions of higher porosity persist [15].

If a paste contains a relatively large amount of fly ash, some ash particles will remain embedded in the system even after a long period of time. These particles, though mostly etched, will retain the spherical morphology typical of fly ash.

The existence of a porous transition zone between the fly ash particles and the matrix of the reaction products suggests that the bonding between these two phases may be weak at early ages. Subsequent densification of these regions indicates that bonding improves as curing continues. Depending on the chemical and mineralogical composition and the particle size distribution of the fly ash used, the microstructure of the cement paste incorporating fly ash may vary depending upon the type and brand of fly ash used and the maturity of the paste.

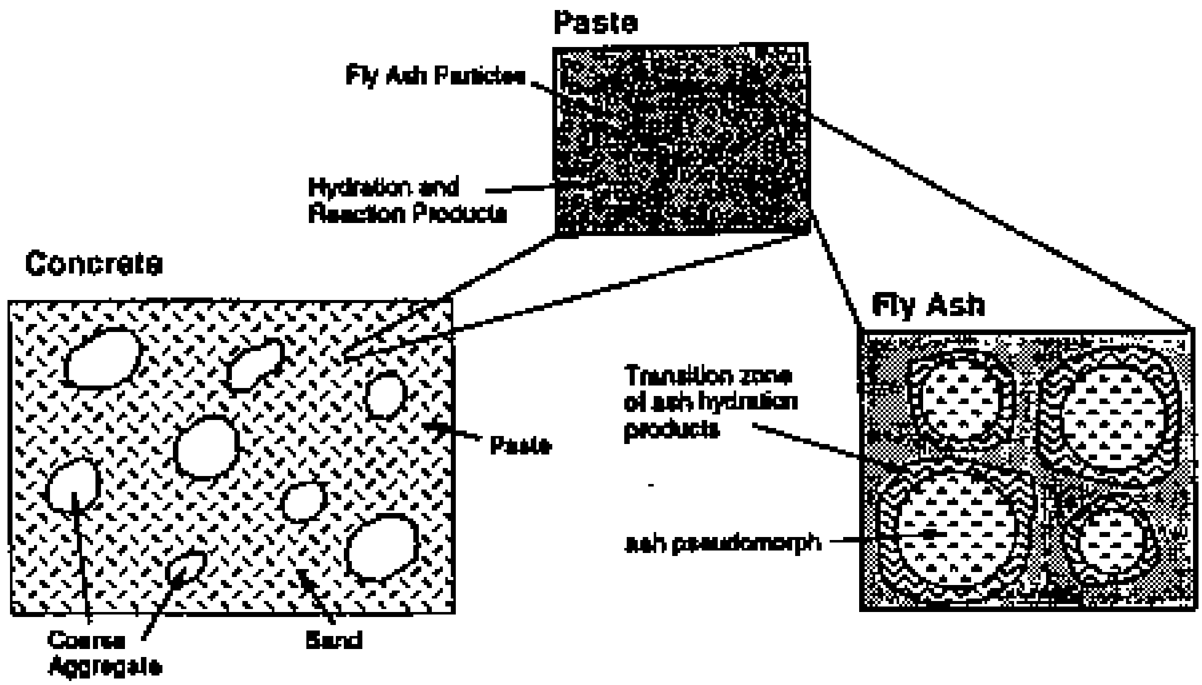

Figure 4-1
Schematic model of fly ash concrete as a composite material; coarse and fine aggregates embedded in the matrix of cement paste, and fly ash particles embedded in the matrix of the hydration and reaction products [16].

When fly ash concrete is exposed to the de-icing salts, especially at early ages, the salt solution penetrates into the concrete through the porous transition zone. Upon freezing, the volume of water increases about 9%. Depending on the space available, this may create a significant hydraulic pressure resulting in cracking and scaling. Also, a further change in the temperature, e.g. from 0 to -20°C or vice versa, may generate significant internal stress at the transition zone due to the differences in the coefficient of thermal expansion of the fly ash particles, ice, and the matrix of the reaction products. Even at later ages, when the thickness of the transition zone between the fly ash particles and the matrix of the reaction products is reduced to zero, the change of temperature may still generate significant internal stress at the transition zone. The microstructure of the cement paste incorporating fly ash at the on-set of the freezing and thawing in the presence of the de-icing salts, therefore, has substantial effect on the scaling resistance of concrete.

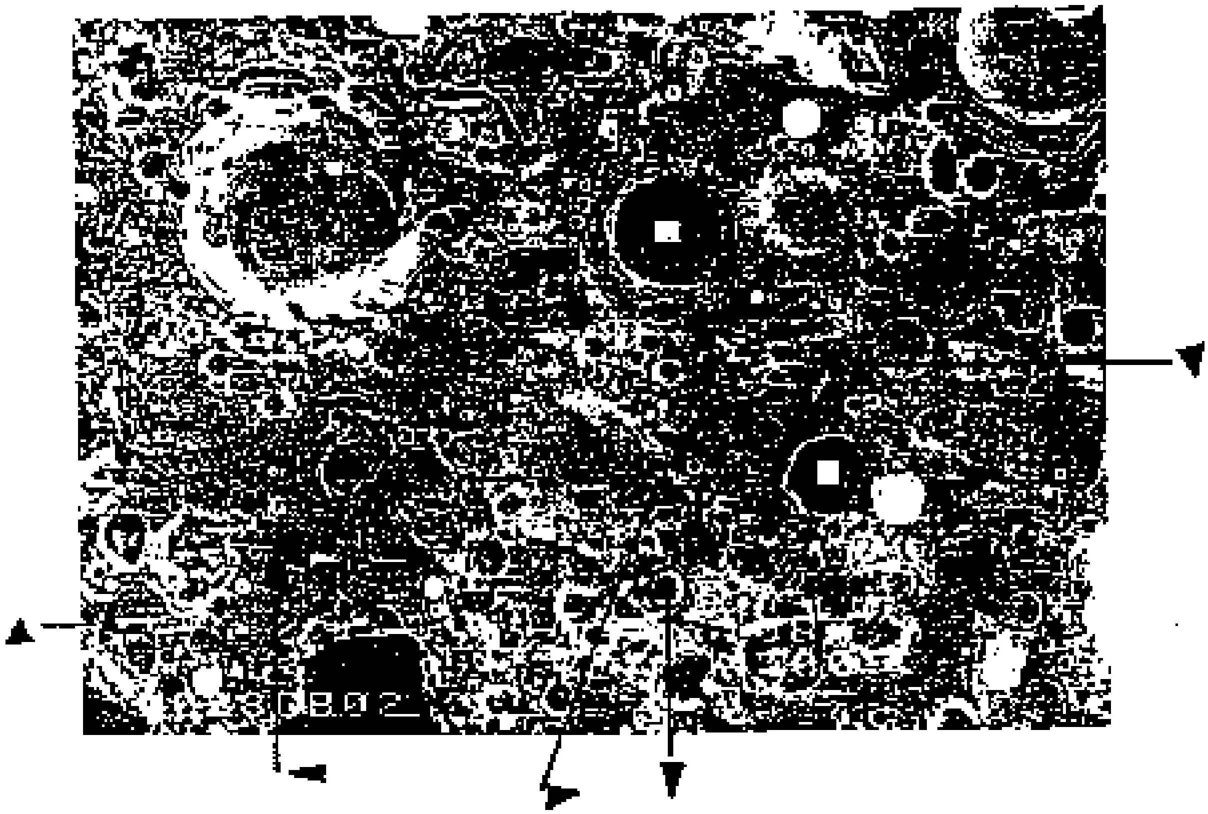

Figure 4-2
Backscatterd electron image (BEI) of a polished section of a paste with 56% Class F fly ash cured for 28 days. The full horizontal frame of the image is 230 µm [15]. Porous zone around some fly ash particles (areas marked with).

The microstructure of the surface layer of the concrete differs from that of the bulk concrete due to bleeding and drying; the bleeding will result in higher w/c of the surface layer, and the drying will retard hydration of cement and pozzolanic activity of fly ash. Both of these, either alone or in combination, will also affect the concrete resistance to the de-icing salt scaling.

The increase in the de-icing salt scaling of concrete incorporating large volumes of fly ash is due to the fact that at higher amounts of fly ash, the volume available for the surrounding hydration and reaction products is reduced, and the volume of the weaker transition zone is increased. At a certain fly ash percentage, the transition zones overlap and create weak areas that are more susceptible to cracking.

Nasser and Ghosh [17] have also pointed out that with an increase in the fly ash content, the presence of unreacted fly ash particles, that do not bond well with the matrix of the reaction products, weaken the bonding, and thus adversely affect the frost resistance of such concrete.

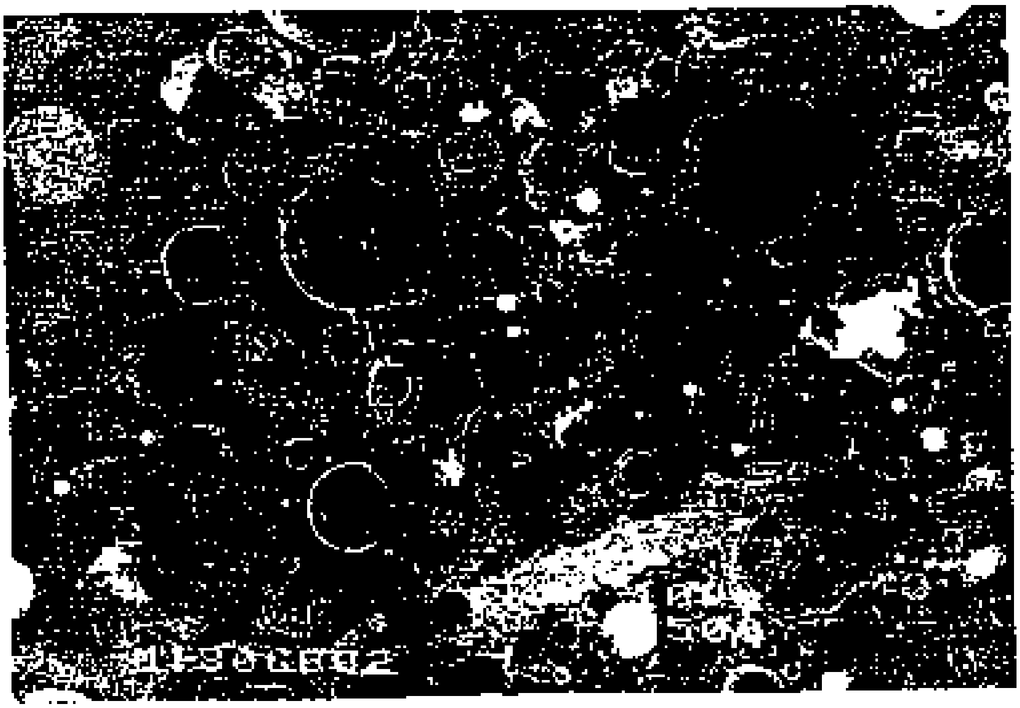

Figure 4-3
Backscattered electron image (BEI) of a polished section of paste with 56% Class F fly ash cured for 180 days. The full horizontal frane of the image is 230 μm [15].

5

FINITE ELEMENT ANALYSIS OF THE INTERNAL STRESSES AT THE TRANSITION ZONE

The cement paste with fly ash may be considered as a composite material consisting of three phases: the fly ash particles, the surrounding matrix of the cement hydration and pozzolanic reaction products, and the transition zone between these two phases. The density, coefficient of thermal expansion, and deformation capacity, i.e. the modulus of elasticity and Poisson's ratio of these three phases are very different.

Figure 5-1 shows a simple cubic unit cell model to simulate the cement paste with fly ash exposed to freezing and thawing cycling in the presence of the de-icing salts, and Figs. 5-2 and 5-3 show the finite element analysis results of the magnitude and direction of the maximum principal stresses at the transition zone of a unit cell containing a fly ash particle. It is assumed that the unit cell experiences a temperature rise of 20°C (36°F), but the transition zone is filled with ice and the temperature rise does not cause any phase change from the ice to water. The top surface of the unit cell is exposed to the salt and is free of external constraint; the four side surfaces and the bottom surface are restrained by the surrounding material.

The following additional assumptions have been made for the calculation:

- fly ash particles are distributed uniformly in the cement paste
- the diameter of the fly ash particles is 10 µm (0.0004 in.)
- the thickness of the transition zone between the fly ash particle and the matrix of the cement hydration and pozzolanic reaction products is 0.5 µm (0.00002 in.)
- the cement paste contains 30% fly ash by volume

The physical constants of the fly ash, the cement paste, and the ice used for the calculation of the stresses are given in Tables 5-1 and 5-2.

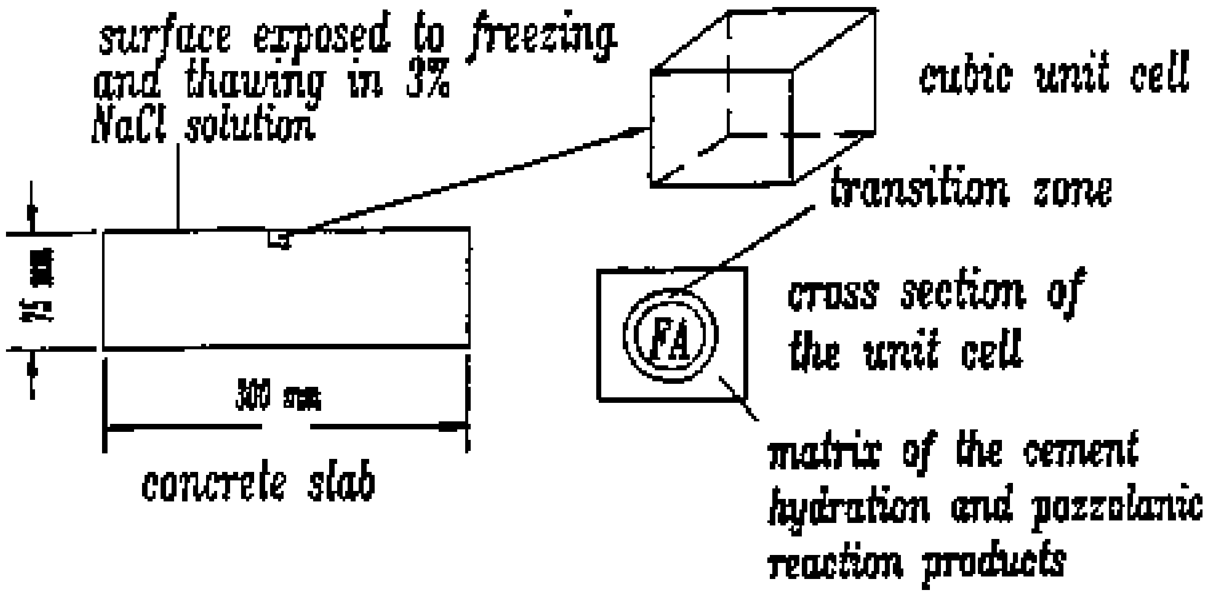

Figure 5-1
A simple cubic model to simulate the fly ash concrete exposed to freezing and thawing cycling in the presence of the de-icing salt.

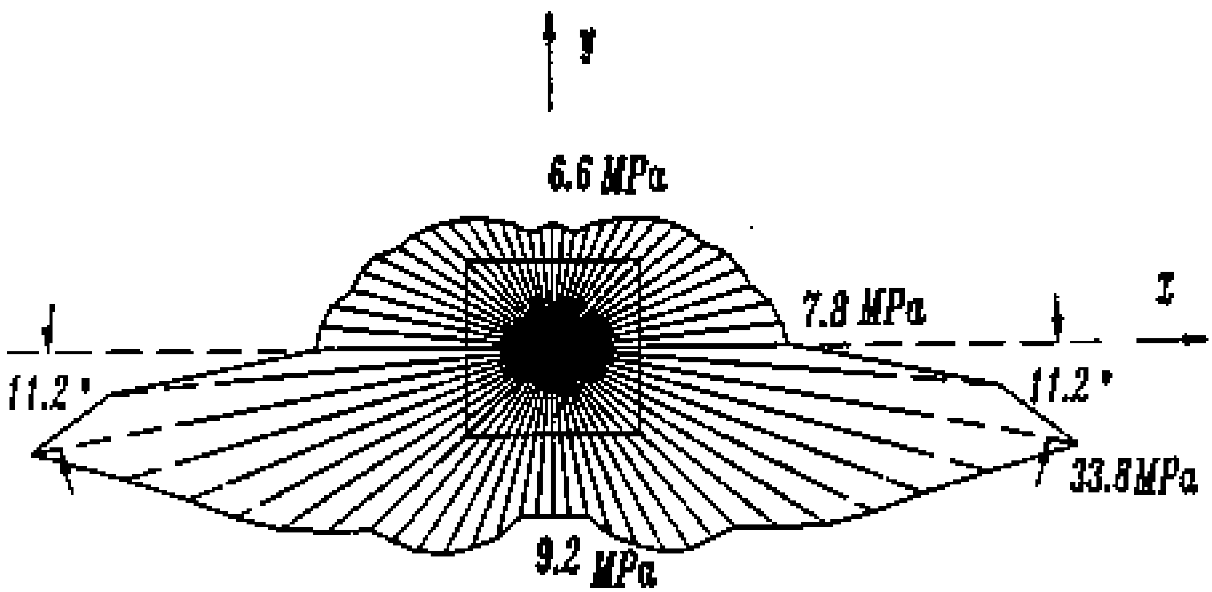

Figure 5-2
Magnitude of the maximum principal stress at the transition zone between the fly ash particle and the matrix of cement hydration and pozzolanic reaction products.

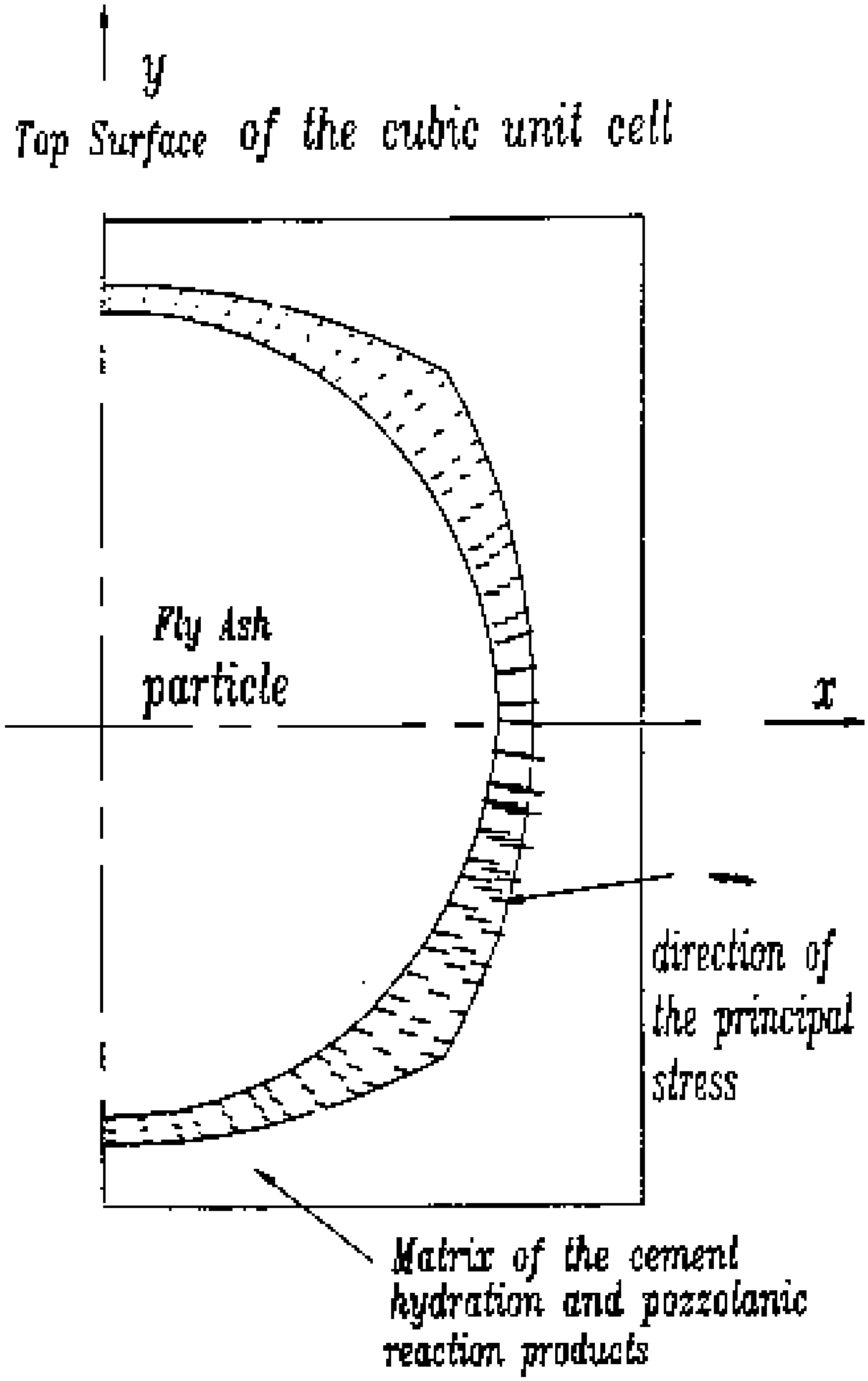

Figure 5-3
Direction of the maximum principal stress at the transition zone between the fly ash particle and the matrix of the cement hydration and pozzolanic reaction products of the unit cell.

From Fig. 5-2, it can be seen that a temperature change generates great tensile stresses at the transition zone between the fly ash particle and the surrounding matrix. The largest stresses are 33.8 Mpa (4900 psi) at the transition zone between the bottom half of the fly ash particle and the surrounding matrix at -11.2° and -168.8° in a Cartesian coordinate. The direction of the stresses in these areas are almost perpendicular to the surface of the fly ash particle (Fig. 5-3). Because the transition zone has higher porosity than the fly ash particle and the surrounding matrix, it is likely the weakest part of the paste. When the tensile stresses exceed the tensile strength of the cement paste which is generally lower than 10 Mpa (1450 psi), cracks are initiated. As the top surface of the unit cell is free of any constraint, and all the other five faces of the unit cell are constrained by the surrounding material, cracks will likely appear first at the transition zone between the bottom half, and then the top half, of the fly ash particles and the surrounding matrix, resulting in progressive scaling layer by layer.

At later ages when the transition zone is reduced to zero, the model shown in Fig. 5-1 can be revised to include two phases: the residual fly ash particle and the matrix of the reaction products (Fig. 5-4). If the same assumptions be made as above, the finite element analysis results of the magnitude of the maximum principal stresses at the interface between these two phases is shown in Fig. 5-5. The directions of the stresses are the same as those shown in Fig.5-3.

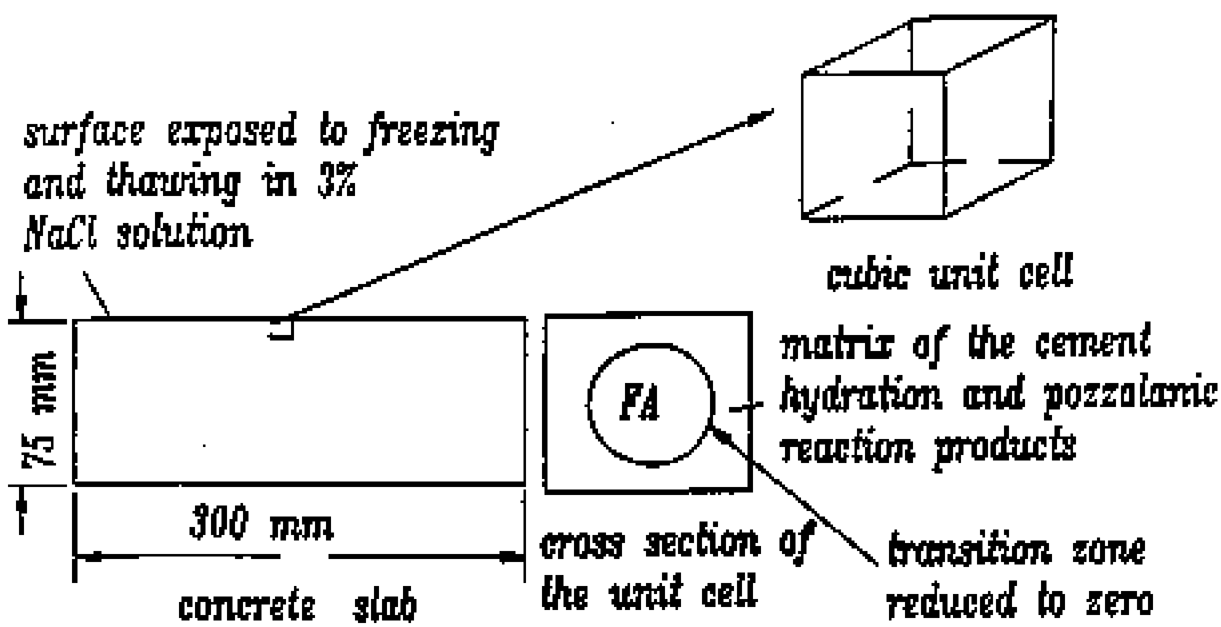

Figure 5-4
A simple cubic init cell model to simulate the fly ash concrete at later ages exposed to freezing and thawing cycling in the presence of the de-icing salt.

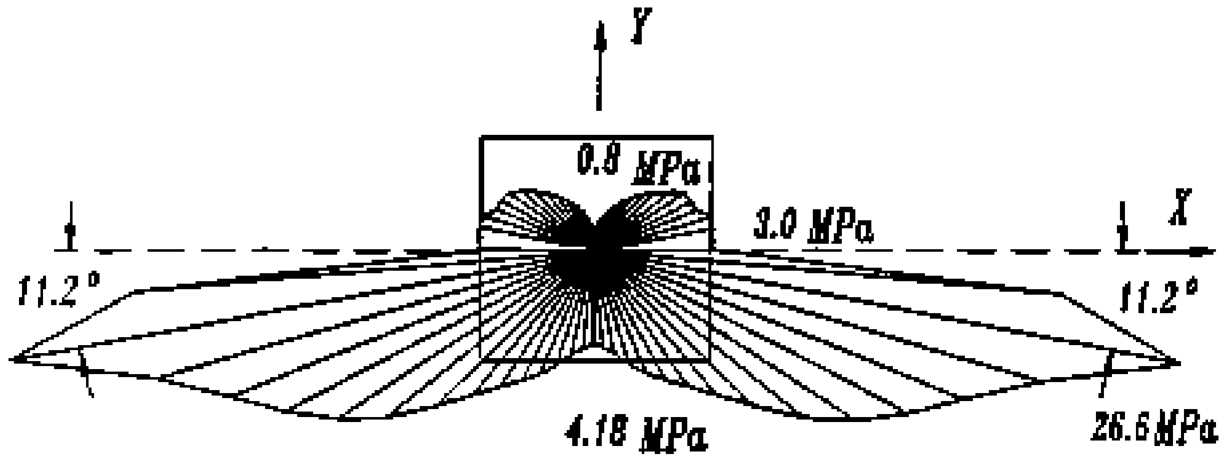

Figure 5-5
Magnitude of the maximum principal stress at the transition zone between the fly ash particle and the matrix of cement hydration and pozzolanic reaction products.

Table 5-1
Material properties used in finite element analysis. (SI units)

	Elastic modulus, GPa	Poisson's ratio	Thermal expansion coefficient, 10^{-6}/°C
Cement paste	20 [18]	0.16 [18]	10 [19]
Fly ash particles	143 [20]	0.2 [19]	10 [19]
Ice [21]	9	0.31	50

Comparing Fig. 5-2 and Fig. 5-5, it is clear that the maximum principal stresses at the transition zone are reduced with decreasing thickness of this zone as a result of the pozzolanic reaction. However, the largest stresses are still 26.6 MPa (3860 psi) at the transition zone between the bottom half of the fly ash particle and the surrounding matrix at -11.2° and -168.8° in the Cartesian coordinate, great enough to cause cracking. It should be mentioned that as the progress of the pozzolanic reaction reduces the density of the fly ash particle and increases the density of the matrix, the differences in the elastic modulus, poisson ratio, and coefficient of thermal expansion between these two phases may be reduced. Therefore, the actual stresses at the interface may be lower than those shown in Fig. 5-5.

Table 5-2
Material properties used in finite element analysis.

	Elastic modulus, psi	Poisson's ratio	Thermal expansion coefficient, 10^{-6}/°F
Cement paste	2,900,000 [18]	0.16 [18]	5.6 [19]
Fly ash particles	20,735,000 [20]	0.2 [19]	5.6 [19]
Ice [21]	1,305,000	0.31	27.8

Figure 5-6 is a scanning electron micrograph of a crack pattern of a fly ash concrete exposed to five cycles of freezing and thawing in the presence of the de-icing salts. The crack pattern appears to be consistent with the stress analysis discussed above.

If the concrete is saturated, the internal stresses generated by the phase change from water to ice at the transition zone will be even greater.

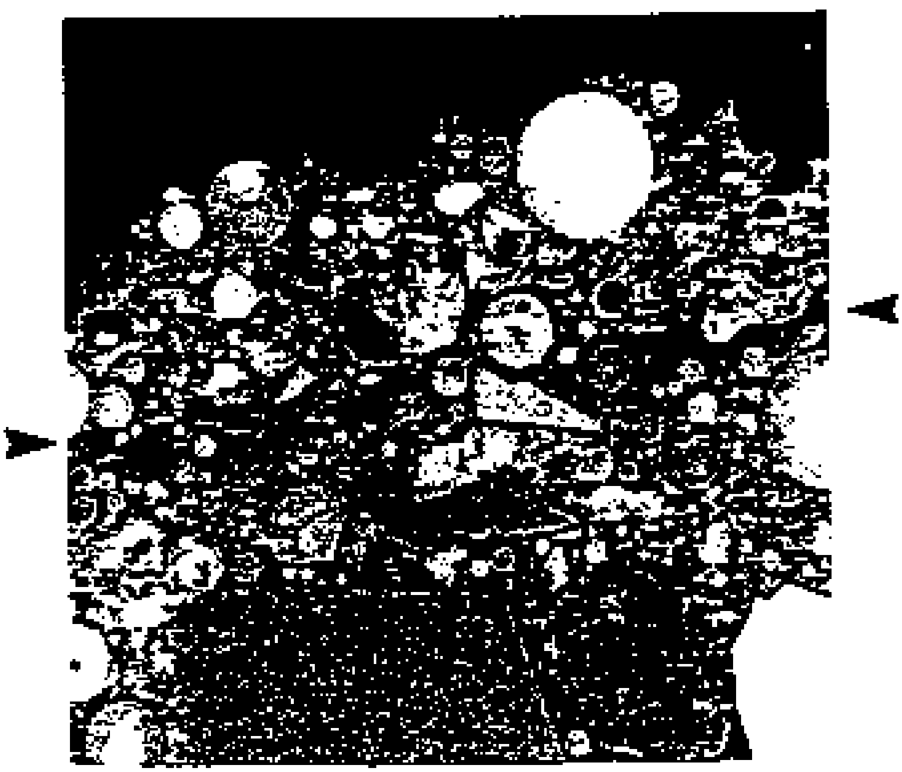

Figure 5-6
Scanning electron micrograph of the crack pattern of the HVFA concrete (Mixture 8) exposed to the de-icing salt after five cycles of freezing and thawing. The full horizontal frame of the image is 329 µm.

6

SUMMARY OF OBSERVATIONS

1. The water-to-cement ratio (W/C) of concrete has significant effect on the resistance of the concrete to the de-icing salt scaling; for moist cured control concrete without fly ash, the W/C should be ≤0.40 for satisfactory resistance to de-icing salt scaling.

2. The type and the amount of fly ash used and the water-to-cementitious materials ratio (W/CM) of the concrete affect considerably the de-icing salt scaling resistance of concrete. In general, the resistance to the de-icing salt scaling decreases with increasing amounts of fly ash and increasing W/CM.

3. For the same water-to-cementitious materials ratio, the fly ash concrete showed more scaling than the reference concrete. However, concretes incorporating up to 35 percent of the ASTM Class F fly ash produced with eastern bituminous coal (Belews Creek), and having a W/(C+FA) of 0.40 or less performed well in the scaling test when tested using the standard 14-day moist-curing and 14-day air-drying periods (ASTM C 672). For concrete incorporating 25% of the ASTM Class C fly ash produced with western sub-bituminous coal from the Powder River Basin (Pleasant Prairie), concrete did not perform satisfactorily when the w/cm was ≥0.40. For concrete incorporating 25% of the ASTM Class F fly ash produced with central Pennsylvania coal (Montour), the concrete had severe scaling regardless of the W/CM investigated.

4. The effect of the duration of the moist-curing period on the scaling resistance of concrete is not clear; increasing the duration of moist curing improved slightly the scaling resistance in some cases but was significantly detrimental in other cases. Extended moist-curing periods beyond 14 days do not insure increased resistance to de-icing salt scaling for concrete. This is particularly so for fly ash concrete.

5. The amount of scaling residue increased significantly with an increase in the duration of the drying period, especially for the fly ash concretes. The drying affects significantly the surface of the slabs and makes them more vulnerable to scaling, possibly through the development of microcracking; this effect seems to be more severe for the fly ash concrete.

6. The performance of the slabs cast vertically was not significantly different from that of the slabs cast horizontally.

7. The use of the curing compounds greatly improved the scaling resistance of all concretes tested but was more beneficial for the fly ash concretes. The much better performance of the slabs treated with curing compounds is probably due to reduced cracking at the surface of the slabs resulting possibly from a more gradual drying of the concrete surface.

8. The microstructure of the cement paste at the on-set of the freezing and thawing appears to affect the de-icing salt scaling of the concrete.

7

CONCLUSIONS

Based on the laboratory tests, for satisfactory performance when exposed to de-icing salts, fly ash concrete should have a W/CM of less than 0.40, and preferably close to 0.35, and the percentage of fly ash should not exceed 25% by weight of the cement.

The use of curing compound is recommended since the laboratory test results demonstrate that it improves significantly the de-icing salt scaling resistance of the concrete, particularly fly ash concrete.

It appears that high levels of fly ash use in concrete result in a greater vulnerability to de-icing salt scaling. This property is aggravated by the procedure used in the de-icing salt scaling test, considering the well documented satisfactory performance in the field. The ASTM test procedure for determining the de-icing salt scaling resistance of the concrete should be modified to better account for field results. A severe exposure to a highly concentrated solution of salt at a two week age is not representative of actual field conditions.

8

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