

Investigation into Freezing-Thawing Durability of Low-Permeability Concrete with and without Air Entraining Agent

National Concrete Pavement
Technology Center



Final Report
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16. Abstract The aim of the present study is to investigate the effect of low-permeability concrete, made with reduced water-to-binder ratios (w/b) and/or supplementary cementitious materials (SCMs), on the need for air entrainment to achieve freezing-thawing (F-T) durability. In the present study, concrete mixes were made with different types of cement (Types I and IP), with or without fly ash replacement (15%), with different water-to-binder ratios (w/b =0.25, 0.35, 0.45 and 0.55), and with or without air entraining agent (AEA). All concrete mixtures were controlled to have a similar slump by using different dosages of superplasticizer. The rapid chloride permeability and F-T durability of the concrete samples were determined according to ASTM C1202 and ASTM C666A, respectively. The air void structure of the concrete was studied using the Air Void Analyzer, RapidAir, and porosity tests (ASTM C642). In addition, the general concrete properties, such as slump, air content, unit weight, and 28-day compressive strength, were evaluated. The results indicate that all concrete mixes with proper air entrainment (ASTM C231 air content $\geq 6\%$) showed good F-T resistance (durability factor $\geq 85\%$). All concrete mixes without AEA showed poor F-T resistance (durability factor $< 40\%$), except for one mix that had very low permeability and high strength. This was the concrete made with Type IP cement and with a w/b of 0.25, which had a permeability of 520 coulombs and a compressive strength of 12,760 psi (88 MPa). There were clear relationships between the F-T durability and hardened concrete properties of non-air entrained concrete. However, such relationships did not exist in concrete with AEA. For concrete with AEA, good F-T durability was associated with an air void spacing factor ≤ 0.28 mm (by AVA) or ≤ 0.22 mm (by RapidAir).					
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1. INTRODUCTION

1.1 Background

In cold climate regions, many concrete pavement deterioration types are associated with cyclic freezing and thawing (F-T) and repeated applications of deicing chemicals. The F-T damages generally result from the volume change involved in ice formation and water migration in concrete, which generate hydraulic and osmotic pressures. For most conventional concretes, proper air entrainment is therefore essential because well-distributed micro-air bubbles can cut the water paths and provide additional spaces for ice to expand, which thus reduces the hydraulic and osmotic pressures.

Researchers and engineers have emphasized that a precondition for concrete to have F-T damage is the existence of freezable water in the concrete. Generally, concrete becomes vulnerable to F-T damage when it reaches a critical saturation condition. In other words, concrete will not be damaged by F-T if the concrete is dry or impermeable. This assumption later becomes a basis of argument about whether high-strength concrete (HSC) or very low permeability concrete needs air entrainment.

Since little water can penetrate into the concrete, HSC or very low permeability concrete rarely reaches its critical saturation condition, and therefore no significant F-T damage should take place. From the microstructure point of view, HSC contains mostly very fine pores. Due to the pore surface tension, the pore water is very difficult to freeze. Because the water in HSC barely freezes, there would be no F-T damage.

Philleo (1987) has pointed out that concrete with very low water-to-binder ratio (w/b) has no capacity for freezable water. All water in the concrete can be used for cement hydration, and proper curing is essential to provide proper hydration so that all spaces in the concrete are filled with hydration products. Thus, the concrete becomes impermeable, and moisture saturation is unlikely under natural exposure conditions. The addition of supplemental cementitious materials (SCMs), especially silica fume, can produce smaller pore sizes in which water cannot freeze at ordinary ambient temperature. Pigeon et al. (1991), in testing the F-T durability of 17 low w/b concrete mixes, have analyzed the influence of various parameters (type of cement, type of aggregate, and curing period) on the limiting w/b value, or the value below which air entraining admixture (AEA) is not required for good F-T durability. The authors reported that the limiting w/b is 0.25 (or 0.30 in certain cases). However, Cohen et al. (1992) has shown that the strength of HSC decreases with the increase of the F-T cycles, which implies that use of AEA is necessary. Bassuoni and Nehdi (2005) have stated that non-air-entrained, low w/b concrete is vulnerable to F-T degradation, although such vulnerability might not be detected using classical frost durability tests.

Currently in Norway, air entrainment is not required for low w/b concrete, while in Canada air entrainment is demanded regardless of w/b (Jacobsen et al. 1996). More research is necessary on this subject to provide proper guidelines for designing and constructing durable concrete.

1.2 Problem Statement

During the last decade, HSC, typically having a w/b lower than 0.30 and used with an application of SCMs, has increasingly been used not only because of the strength demand but also because of concrete durability considerations. Having high density and very low permeability, HSC or low w/b concrete possesses excellent resistance to various deteriorations caused by water, gas, and chemical penetration into the concrete.

High-density and low-permeability concrete rarely becomes saturated, and the water in the very fine capillary voids of the concrete hardly freezes in field exposure conditions (Philleo 1987). Therefore, theoretically, there is no need to require the use of AEA for F-T durability in high-density and low-permeability concrete. The use of AEA could cause notable strength reduction due to the existence of air bubbles. Moreover, it is often difficult to produce a proper and stable entrained air system in HSC due to the dry mixture made with a low w/b and high binder content.

A great deal of research has been conducted to investigate whether the use of AEA in HSC is necessary. Unfortunately, the results are controversial. Some researchers have shown that concrete with low w/b without AEA exhibits excellent F-T resistance, while others indicate that HSC with w/b higher than 0.25 must contain entrained air (Pigeon et. al. 2003; Aitcin 1994; Molhotra 1987; Krumbach et al 1997). These controversial laboratory and field results may result from the difficulties in consistently delivering non-air-entrained low w/b concrete, the deficiency of the standard F-T test method, and the variations in concrete materials and process methods (mixing and curing) used.

The correct answers regarding whether AEA is necessary for low w/b or low-permeability concrete and how low the w/b should be before AEA becomes unnecessary are of practical importance for designing and constructing functional and durable concrete pavements. With the use of blended cements in Iowa, lower permeability concrete has been achieved at normal w/b ratios. The present research is designed to investigate the F-T behaviors of Iowa concrete materials.

1.3 Research Objectives

The major objectives of this study are as follows:

1. To investigate the effects of concrete mixes, made with different types of cement, different w/b, and with and without AEA, on F-T durability
2. To determine the value of the limiting w/b, or the permeability below which AEA becomes unnecessary for good concrete F-T durability
3. To examine the effects of cement type and SCM on the effectiveness of air entrainment and the limiting w/b or permeability values

2. MATERIALS AND METHODS

2.1 Materials

The cementitious materials used in the study were provided by the Iowa Department of Transportation (Iowa DOT). The cementitious materials are Type I and Type IP and Class C fly ash. The Type IP source is a blended cement with 25% Class F fly ash. The chemical composition and compounds of these cementitious materials were determined by XRF and are listed in Table 2.1. The cementitious materials are within the requirements of their respective American Society for Testing Materials (ASTM) specifications.

Table 2.1. Chemical composition and compounds of cementitious materials (%)

	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	SO ₃	K ₂ O	CaO	Fe ₂ O ₃	LOI
Type I	0.15	3.34	4.17	20.20	2.47	0.69	63.20	2.96	2.37
Type IP	0.29	2.87	8.51	30.10	3.38	0.70	48.50	3.17	1.60
Fly Ash - C	1.64	4.87	17.68	31.92	1.68	0.43	30.92	6.54	0.47
	C₃S		C₂S		C₃A		C₄AF		
Type I	64.48		9.27		6.04		9.01		

The freeze-thaw durable limestone coarse aggregate used in this research was obtained from the Ames Quarry, Bed 47 LC, through Martin Marietta Materials. Its nominal maximum size was 25 mm (1 in.). The fine aggregate was river sand from Hallett Materials. The gradation of the fine and coarse aggregates are shown in Figure 2.1. The aggregate properties are given in Table 2.2.

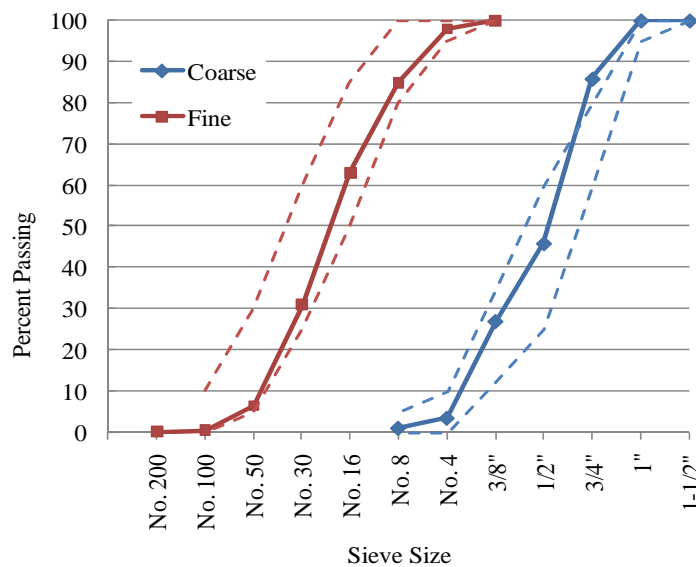


Figure 2.1. Fine and coarse aggregate gradations

Table 2.2. Properties of aggregates

Sieve Size		% Passing (by mass)	
		Limestone, NMSA= 25 mm (1 in.)	River sand (F.M. =3.16)
25 mm	(1 in.)	100.00	-
19 mm	(3/4 in.)	85.85	-
12.5 mm	(1/2 in.)	45.87	-
9.5 mm	(3/8 in.)	26.97	100.00
4.75 mm	(No. 4)	3.46	97.96
2.36 mm	(No. 8)	1.04	84.84
1.18 mm	(No. 16)	-	63.06
600 µm	(No. 30)	-	31.04
300 µm	(No. 50)	-	6.48
150 µm	(No. 100)	-	0.44
Specific gravity		2.66	2.61
Absorption, %		0.72	1.09

The two Iowa DOT mix proportions, (1) C3-WR-C with Type I cement and Class C fly ash and (2) C3-WR with Type IP cement, were modified to obtain concrete mixtures with different w/b (0.25, 0.35, 0.45, 0.55). To obtain different w/b, the amount of water was reduced while all other concrete components were kept the same. All concrete mixtures were controlled to have similar slumps. Different dosages of high-range water reducing agent (HWRA) were applied to the lower w/b mixtures obtain similar slump values. The concrete mix proportions for the different cement types and w/b are given in Table 2.3.

Table 2.3. Concrete mix proportions

Binder	Mix ID	Mix Design, kg/m ³ (pcy)						AEA,	HRWR,	w/c
		Cement	Fly Ash	Water	Fine Agg.	Coarse Agg.	ml/m ³ (oz/cy)	ml/m ³ (oz/cy)		
I-FA	I-FA55	221 (487)	39 (86)	143 (315)	625 (1376)	761 (1674)	166 (4.30)	0	0.55	
	I-FA45	221 (487)	39 (86)	117 (258)	625 (1376)	761 (1674)	166 (4.30)	1316 (34)	0.45	
	I-FA35	221 (487)	39 (86)	91 (201)	625 (1376)	761 (1674)	166 (4.30)	2514 (65)	0.35	
	I-FA25	221 (487)	39 (86)	65 (143)	625 (1376)	761 (1674)	166 (4.30)	6190 (160)	0.25	
IP	IP55	260 (571)	0	143 (314)	627 (1380)	765 (1684)	166 (4.30)	0	0.55	
	IP45	260 (571)	0	117 (257)	627 (1380)	765 (1684)	166 (4.30)	1316 (34)	0.45	
	IP35	260 (571)	0	91 (200)	627 (1380)	765 (1684)	188 (4.85)	2514 (65)	0.35	
	IP25	260 (571)	0	65 (143)	627 (1380)	765 (1684)	221 (5.71)	6190 (160)	0.25	

The HWRA used is Adva Cast 575, from Grace Construction Products. The AEA used is AEA-92 by Euclid Chemical Company.

2.2 Methods

All concrete mixtures were batched based on a standard procedure according to ASTM C192 and were moist-cured for 28 days. The slump, air content, and unit weight of the fresh concrete were measured as the concrete quality control information. The air void analyzer (AVA) was used to determine the volume and size distributions of the entrained air voids in the fresh concrete.

The AVA test was performed according to the test method outlined by Taylor et al. (2006). To set up the AVA, water and glycerol of known viscosity are poured into the riser cylinder. Air bubbles are removed using a brush. The buoyancy recorder is set up at the top of the riser, and the operator ensures that no air is trapped in the collector. Samples are extracted from the fresh concrete using an assembly of a percussion drill, a vibrator cage, and a syringe. The vibrating cage is slowly pushed into the concrete to let the mortar flow into the cage. The operator obtains 20 ml of mortar and fills the syringe. The mortar is injected into the glycerol-filled cylinder. The AVA machine stirs the mortar to release the air bubbles, which rise in the fluid. The AVA takes a maximum of 25 minutes to complete data recording and analysis.

Samples from each mixture were prepared in three 100×200 mm (4×8 in.) cylinders and three 75×100×400 mm (3×4×16 in.) beams for compressive strength and F-T resistance tests, respectively. Six additional cylinders were prepared, three for rapid chloride permeability, two for porosity, and one for RapidAir testing. All hardened concrete properties, including F-T durability, were taken on 28-day-old concrete.

Because of the importance of concrete air void structure in this study, three different tests were conducted for all concrete mixtures: rapid chloride permeability, RapidAir, and porosity. The F-T resistance test was conducted to compare the durability of the concrete with and without air-entrainment.

To measure the air void structure of the concrete, 100×100×10 mm (4×4×3/8 in.) samples were cut from the center of the 100×200 mm (4×8 in.) cylinders. The samples were then polished following ASTM C457. When the samples were flat and smooth, they were coated with a thin film of black dye and let dry. Then, each sample was heated to about 50 °C. A paste of zinc oxide (white in color) was rubbed on the concrete to fill the air voids in the sample. The zinc oxide was then allowed to cool. The excess was scrapped off using a blade, leaving only the zinc oxide in the voids. The result was a black concrete surface with white air voids. Using a microscope and a computer program, the RapidAir device identified white spots (air voids) and provided information on the air void content, spacing factor (SF), and specific surface of the tested sample.

A summary of the proposed tests and related ASTM or American Association of State and Highway Transportation Officials (AASHTO) standards are presented in Table 2.4.

Table 2.4. Test methods and number of samples

Property	Test Methods
Fresh Concrete Properties	
Slump	ASTM C143/ AASHTO T 119
Air content	ASTM C231/ AASHTO T 152
Unit weight	ASTM C138/ AASHTO T 121
AVA	NA
Hardened Concrete Properties	
$f'_{c, 28}$ strength	ASTM C39/ AASHTO T 22
Rapid chloride permeability	ASTM C1202/ AASHTO T 277
Rapid air	ASTM C457
Porosity (boiling) test	ASTM C642
F-T resistance	ASTM C666/ AASHTO T 161

3. TEST RESULTS

The results for the various tests of the different mixes are given in the following sections. In cases where the Iowa DOT designation is not used (and for brevity), I-FA and I-FA-AEA will denote concrete with Type I cement plus Class C fly ash, without and with AEA, respectively. IP and IP-AEA will denote concrete plus Type IP cement, without and with AEA, respectively. When I-FA or IP is followed by a number, the number indicates the w/b of the concrete. This notation will also be adopted in other sections of this report.

3.1 Fresh Concrete Properties

Slump, Air Content, and Unit Weight

The fresh concrete slumps, air contents, and unit weights are given in Table 3.1. The range of the reference slumps (w/b = 0.55) is from 175 to 200 mm (7 to 8 in.). The slumps for the different types of mixes are similar to their respective references, with a maximum difference of 31 mm (1.25 in.). These maxima are on the lowest w/b (0.25), where controlling the workability becomes much more difficult.

From the results given in Table 3.1, concrete without AEA has 1.5% to 2.8% air. I-FA-AEA has 7% to 8.2% air, while IP-AEA has 6% to 8% air. All I-FA concrete mixtures with AEA had the same dosage of admixture, while IP concrete mixtures required more AEA with decreasing w/b, as shown in Table 2.3. I-FA-AEA shows higher and more consistent air content than IP-AEA. The unit weights of the fresh concrete mixes were measured using a 0.007 m³ (0.25 ft³) cylindrical mold.

The unit weights for the I-FA mixtures ranged from 2,262 to 2,326 kg/m³ (141 to 145 pcf), where the low w/b is slightly higher than the reference mix (w/b = 0.55). In the case of the IP concrete, the range of unit weights is much larger, 2,278 to 2,400 kg/m³ (142 to 149.6 pcf), with IP25 having the highest unit weight of 2,518 kg/m³ (157 pcf).

Table 3.1. Slump, air content, and unit weight of concrete mixtures

	Slump, mm (in) (C143)	Air, % (C231)	Unit Weight, kg/m ³ (pcf) (C138)
Concrete without AEA			
I-FA55	181.2 (7.25)	1.5	2284 (142.4)
I-FA45	187.5 (7.50)	1.8	2262 (141.0)
I-FA35	162.5 (6.50)	2.2	2306 (143.8)
I-FA25	150.0 (6.00)	2.8	2318 (144.5)
IP55	175.0 (7.00)	1.5	2310 (144.0)
IP45	168.8 (6.75)	2.5	2278 (142.0)
IP35	162.5 (6.50)	2.2	2374 (148.0)
IP25	200.0 (8.00)	1.5	2518 (157.0)
Concrete with AEA			
I-FA55-AEA	193.8 (7.75)	7.8	2278 (142.0)
I-FA45-AEA	187.5 (7.50)	7.0	2270 (141.5)
I-FA35-AEA	175.0 (7.00)	8.0	2302 (143.5)
I-FA25-AEA	175.0 (7.00)	8.2	2326 (145.0)
IP55-AEA	200.0 (8.00)	6.0	2276 (141.9)
IP45-AEA	200.0 (8.00)	8.0	2278 (142.0)
IP35-AEA	200.0 (8.00)	7.0	2318 (144.5)
IP25-AEA	187.5 (7.50)	7.5	2400 (149.6)

Air Void Structure by AVA

The air contents, specific surfaces, and SFs of the concrete mixtures were obtained using the AVA and are given in Table 3.2. The AVA measures air voids with a size equal to or less than 2 mm. In concrete, only the small-size air voids (≤ 0.3 mm or $300 \mu\text{m}$) significantly benefit the F-T resistance. Therefore, both the total air (≤ 2 mm) and small air ($\leq 300 \mu\text{m}$) content measurements are presented. Figure 3.1 shows the amount of air by the size of the void for mixtures without AEA and with AEA.

The amount of air in the concrete without AEA ranges from 0.2% to 2.4%. For I-FA-AEA, the entrained air is from 5.9% to 9.3%. For the IP mixtures with AEA, the amount of air varies from 5.6% to 9.3%, except for IP55-AEA, whose air measured only 2.8%. Since AVA measures only air voids with a size equal or less than 2 mm, the total air content measured by AVA is generally less than that measured by the ASTM C231 tests (Wang et al. 2008). It is not clear at this time

why some mixtures in the present study had higher AVA total air content than total air content measured by C231.

To be able to withstand a great number of F-T cycles, the air content of air entrained concrete with a low w/b ratio should be between 5% to 8% (Woods 1956). In addition to this value, experience shows that $> 6\% \pm 1\%$ air, specific surface $\geq 24 \text{ mm}^2/\text{mm}^3$, and $\text{SF} \leq 0.20 \text{ mm}$ would be expected to give good concrete F-T resistance (Tanesi and Meininger 2006). In a recent study by Wang et al. (2008), it was found that concrete with $\text{SF} \leq 0.3 \text{ mm}$ measured by AVA would be acceptable for F-T durability because this SF criterion ($\text{SF} \leq 0.3 \text{ mm}$) from an AVA test is equivalent to the criterion ($\text{SF} \leq 0.2 \text{ mm}$) from the ASTM C457 test method. Based on this, mixtures with AEA have sufficient air entrainment for F-T durability, while mixtures without AEA do not.

Table 3.2. Air void parameters of fresh concrete from AVA tests

	Total Air % (size $\leq 2\text{mm}$)	Small Air, % (size $\leq 300 \mu\text{m}$)	Specific surface, mm^{-1}	Spacing factor, mm
Concrete without AEA				
I-FA55	0.3	0.06	16.9	1.07
I-FA45	1.8	0.07	6.2	1.36
I-FA35	0.8	0.10	10.3	1.11
I-FA25	1.0	0.05	9.5	1.02
IP55	0.2	0.05	14.0	1.43
IP45	0.5	0.00	7.6	1.86
IP35	2.4	0.80	18.9	0.37
IP25	1.5	0.08	8.1	1.03
Concrete with AEA				
I-FA55-AEA	5.9	2.47	21.5	0.24
I-FA45-AEA	9.3	4.50	25.4	0.14
I-FA35-AEA	8.0	4.43	31.0	0.13
I-FA25-AEA	7.7	1.96	17.2	0.20
IP55-AEA	2.8	1.44	26.1	0.28
IP45-AEA	8.2	4.55	31.0	0.13
IP35-AEA	5.6	1.62	17.3	0.28
IP25-AEA	9.3	6.54	28.4	0.10

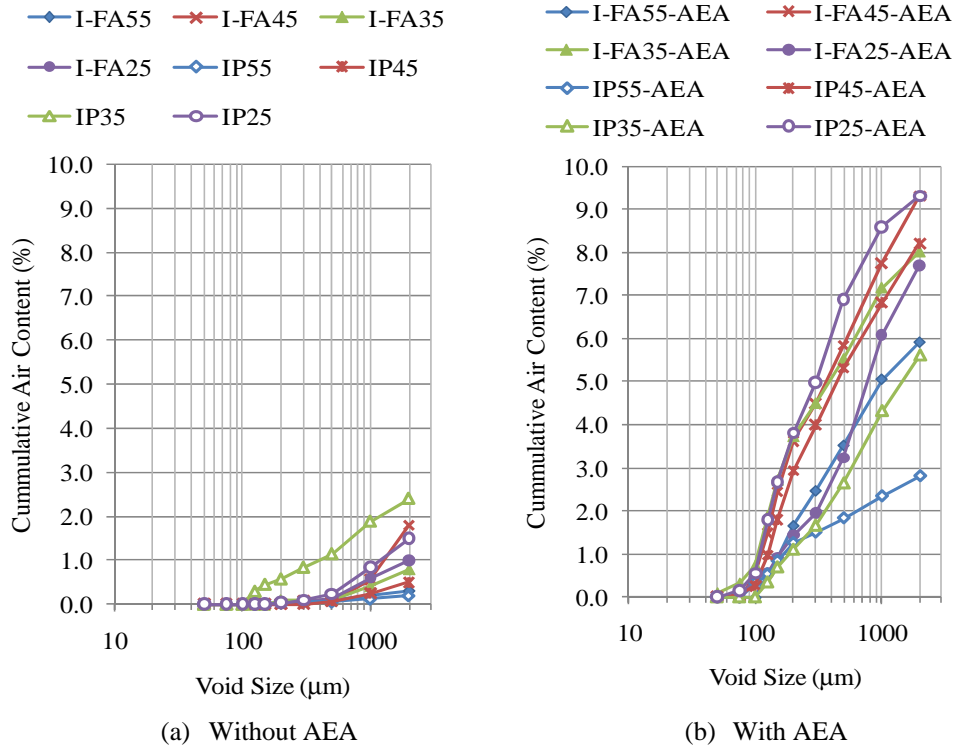


Figure 3.1. Cumulative air content by void size for mixtures, measured by AVA

3.2 Hardened Concrete Properties

28th Day Compressive Strength, Rapid Chloride Permeability, and Porosity

The average 28th day compressive strengths of the concrete cylinder samples are given in Table 3.3. The concrete mixes without air entrainment have higher strengths than their air entrained counterparts. The difference in strengths of the air entrained and non-air entrained mixes is much larger for the I-FA samples than for the IP samples. It is also obvious that the compressive strength of IP25 is much larger than all the other results.

The rapid chloride permeability test measures the electrical conductance of a concrete sample to indicate its permeability to chloride ion penetration. The lower the amount of charge is passed through the concrete, the less permeable the concrete is to chloride ion penetration. The permeability results for the concrete samples are shown in Table 3.3. In the I-FA samples, the permeability values for $w/b = 0.55$ and $w/b = 0.45$ mixes tend to be much greater than the permeability values of the mixes with lower w/b ratios. These samples' permeability values range from high to very low, going from $w/b = 0.55$ to 0.25 . For the IP samples, the permeability differs only from moderate to very low. It is interesting to note that the air entrained samples are more impermeable than their non-air entrained counterparts, which could be due to the slightly higher slump for IP-AEA.

The porosity obtained in the boiling test is the amount of permeable voids in the concrete samples at the age of 28 days. Table 3.3 gives the porosity of the concrete samples. The amount of permeable voids in the samples with AEA is greater than the amount in the non-air entrained samples. The difference in porosity of I-FA and I-FA-AEA is larger than the difference between IP and IP-AEA.

Table 3.3. Properties of hardened concrete

	28-day compressive strengths, MPa (psi)	Rapid chloride permeability, coulombs	Porosity, %
Concrete without AEA			
I-FA55	46.4 (6730)	4300	5.6
I-FA45	54.4 (7890)	3220	6.6
I-FA35	58.6 (8500)	960	5.5
I-FA25	61.0 (8850)	480	4.3
IP55	43.6 (6320)	2080	13.0
IP45	51.8 (7510)	1720	10.5
IP35	54.1 (7840)	1320	8.1
IP25	88.0 (12760)	520	5.0
Concrete with AEA			
I-FA55-AEA	42.4 (6150)	5090	12.7
I-FA45-AEA	47.4 (6870)	3920	9.9
I-FA35-AEA	52.2 (7570)	1160	11.0
I-FA25-AEA	55.5 (8050)	660	10.1
IP55-AEA	31.3 (4540)	1290	13.3
IP45-AEA	39.3 (5690)	1290	11.9
IP35-AEA	49.3 (7150)	1070	11.0
IP25-AEA	57.5 (8330)	350	9.4

Air Void Structure by RapidAir

The results from the RapidAir tests performed on 28-day-old samples are given in Table 3.4. Different from AVA device, the RapidAir equipment measures all voids observed under an optical microscope and considers all air void sizes. In Table 3.4, both the total air and small air ($\leq 300 \mu\text{m}$) content measurements are presented so that the results can be compared to the results in Table 3.2. Considering generally accepted limits for a satisfactory air void system for F-T resistance (Tanesi and Meininger 2006), the concrete samples with AEA would provide adequate F-T resistance.

The air content of mixtures without AEA ranges from 0.4% to 4.1%, while mixtures with AEA have 5.3% to 9.1% air. The maximum SF for mixtures with AEA is 0.22 mm⁻¹, while the SF ranges from 0.29 to 0.83 mm⁻¹ for mixtures without AEA. Figure 3.2 shows the cumulative distribution of the percentage of air according to the size of the air void.

Table 3.4. Air void parameters of fresh concrete from rapid air tests

	Total Air % (size ≤ 3mm)	Small Air, % (size ≤ 300 μm)	Specific surface, mm⁻¹	Spacing factor, mm
Without AEA				
I-FA55	1.5	0.39	18.4	0.50
I-FA45	1.6	0.43	17.7	0.49
I-FA35	4.1	0.63	9.6	0.58
I-FA25	3.0	1.13	20.9	0.29
IP55	0.4	0.16	21.3	0.81
IP45	1.3	0.29	13.6	0.76
IP35	2.7	0.97	20.7	0.34
IP25	1.5	0.24	10.5	0.83
With AEA				
I-FA55-AEA	5.3	3.02	25.8	0.21
I-FA45-AEA	8.2	3.63	21.4	0.19
I-FA35-AEA	7.0	2.85	22.1	0.20
I-FA25-AEA	6.7	2.15	19.0	0.22
IP55-AEA	6.7	3.00	22.6	0.22
IP45-AEA	9.1	5.26	27.6	0.14
IP35-AEA	6.2	3.13	24.2	0.19
IP25-AEA	7.1	3.84	28.1	0.14

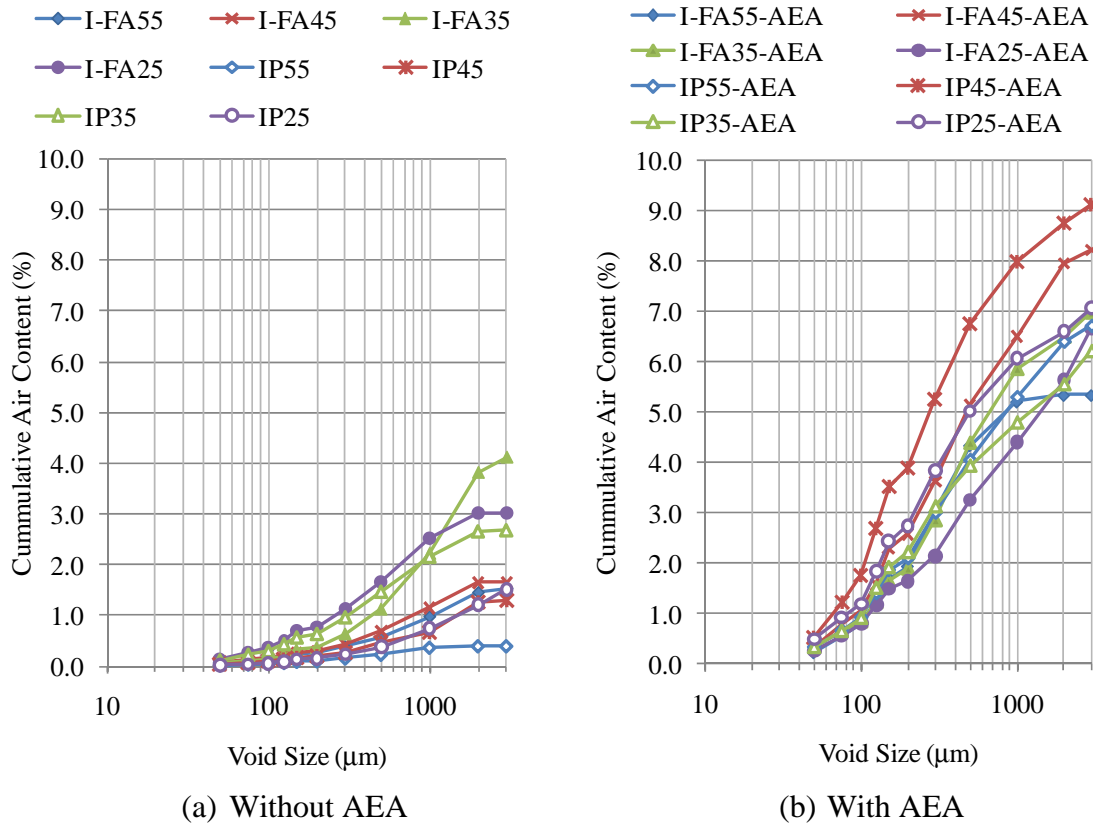


Figure 3.2. Cumulative air content by void size for mixtures, measured by RapidAir

F-T Durability

Concrete beams were subjected to F-T cycling after a 28-day standard fog-room curing. The relative dynamic modulus (RDM) values of the concrete beams and the number of F-T cycles are shown in Figure 3.3. In cases where the samples deteriorated excessively, the dynamic modulus was taken until the deterioration rendered the sample immeasurable. The data show that the terminal RDM of the samples without AEA increased with decreasing w/b. Except for mixtures with w/b = 0.25, all of the beam samples had completely deteriorated before reaching 300 F-T cycles. At 300 cycles, I-FA25 and IP25 had RDM values equal to 34% and 94%, respectively. The I-FA-AEA samples had RDM values at 300 cycles of 92% to 95%, while the IP-AEA had a wider range of final values, 87% to 96%.

The durability factors of the concrete beam samples are shown in Table 3.5. The minimum RDM is 50%, and the maximum number of F-T cycles is 300. The F-T durability of the samples without AEA increased with decreasing w/b. For the air entrained samples, because the RDM values were all greater than 50% after 300 F-T cycles, the durability factors were the same as the RDMs.

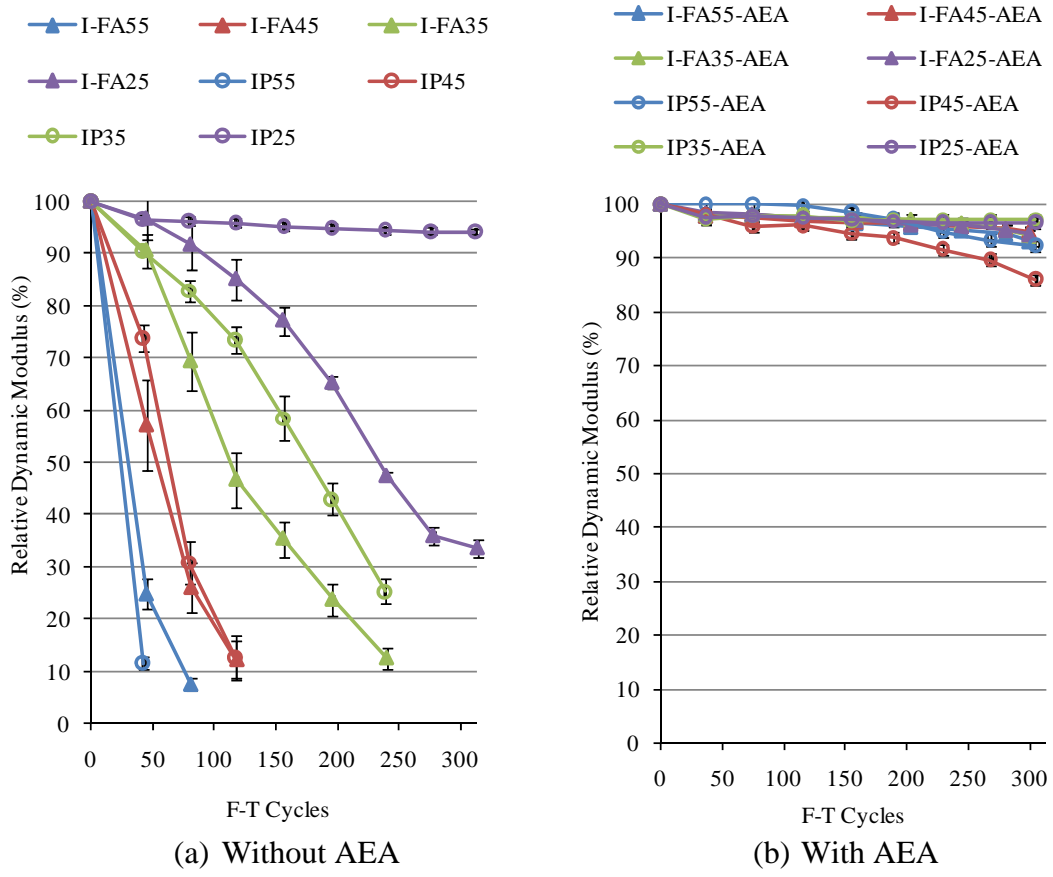


Figure 3.3. RDM for concrete with and without AEA

Table 3.5. RDM and durability factors of beams

	Relative Dynamic Modulus (%)	Durability Factor (%)
Concrete without AEA		
I-FA55	8	5
I-FA45	12	9
I-FA35	12	19
I-FA25	34	39
IP55	12	4
IP45	13	10
IP35	25	30
IP25	94	94
Concrete with AEA		
I-FA55-AEA	92	93
I-FA45-AEA	95	95
I-FA35-AEA	94	94
I-FA25-AEA	94	95
IP55-AEA	92	92
IP45-AEA	87	87
IP35-AEA	96	96
IP25-AEA	95	95

4. DATA ANALYSIS

Many factors can affect the F-T durability of concrete: (1) the amount and structure of entrained air, (2) the permeability or porosity of the concrete, (3) existing defects, (4) the F-T durability of the aggregates (5) curing and strength, and (5) surface finish. The following discussion relates the measured F-T durability of the concrete beam samples to the amount and structure of entrained air, permeability and porosity, and w/b. The same type of aggregate was used for all samples, and thus all have the same F-T durability. All samples were cured for 28 days and had no existing defects before testing. The F-T beams had five sides smooth because of the steel mold, while one side was finished using a straight edge. In the discussion below, the different properties that affect F-T durability are compared individually to the durability factors of the concrete samples.

4.1 Relationship between Air Void Parameters

Figure 4.1 illustrates the relationships between the different air void parameters measured by AVA. Figure 4.1(a) shows that SF decreased with increasing air content. In this figure, the air content in the small air voids is shown because this air content has a better relationship to SF ($R^2=0.96$) than total air content. When the total AVA air content is considered, a similar relationship still exists, but its R^2 value decreases to 0.83. Figure 4.1(b) shows that SF also decreases with increasing specific surface. Based on Figure 4.1(b), the AVA-measured specific surface will be approximately $20 \text{ mm}^2/\text{mm}^3$ when the SF is 0.3 mm.

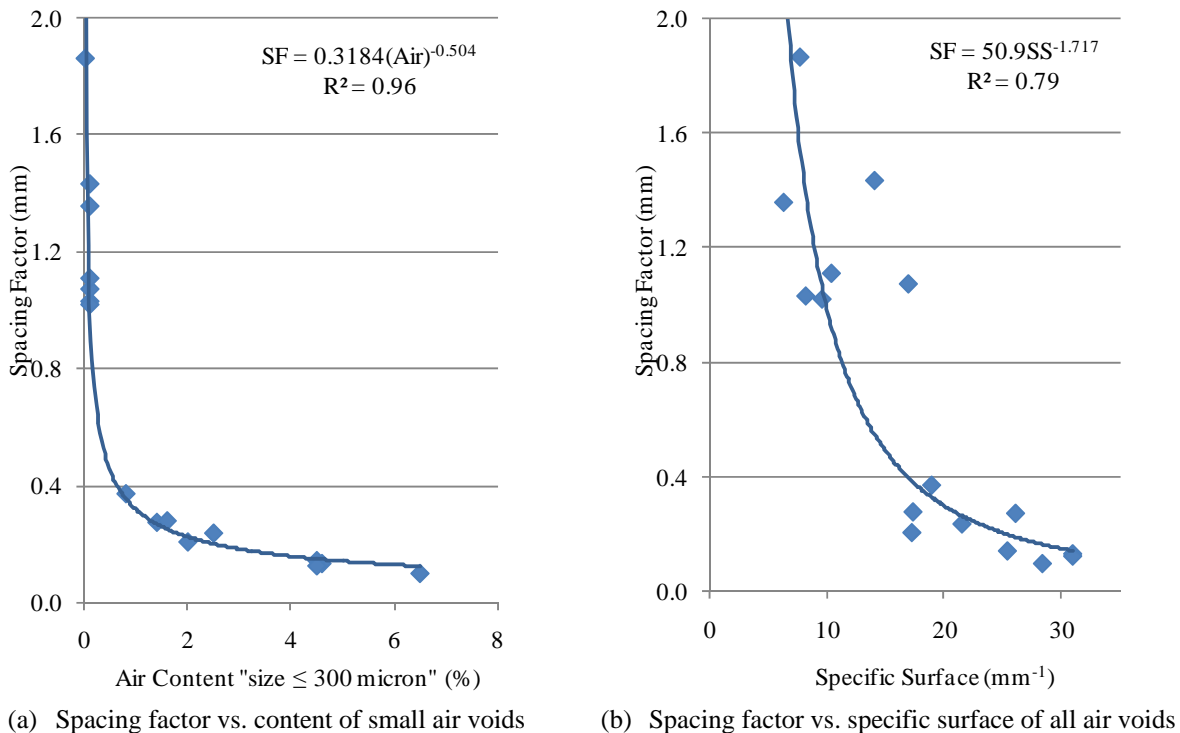


Figure 4.1. Relationships between air void parameters measured by AVA

Figure 4.2 illustrates the relationships between the air void parameters measured by RapidAir; the trends are the same as those illustrated in Figure 4.1. In Figure 4.2(b), one data point had a higher SF and specific surface than other data points. Excluding this outlier in the model improves the fit from $R^2 = 0.61$ to $R^2 = 0.79$.

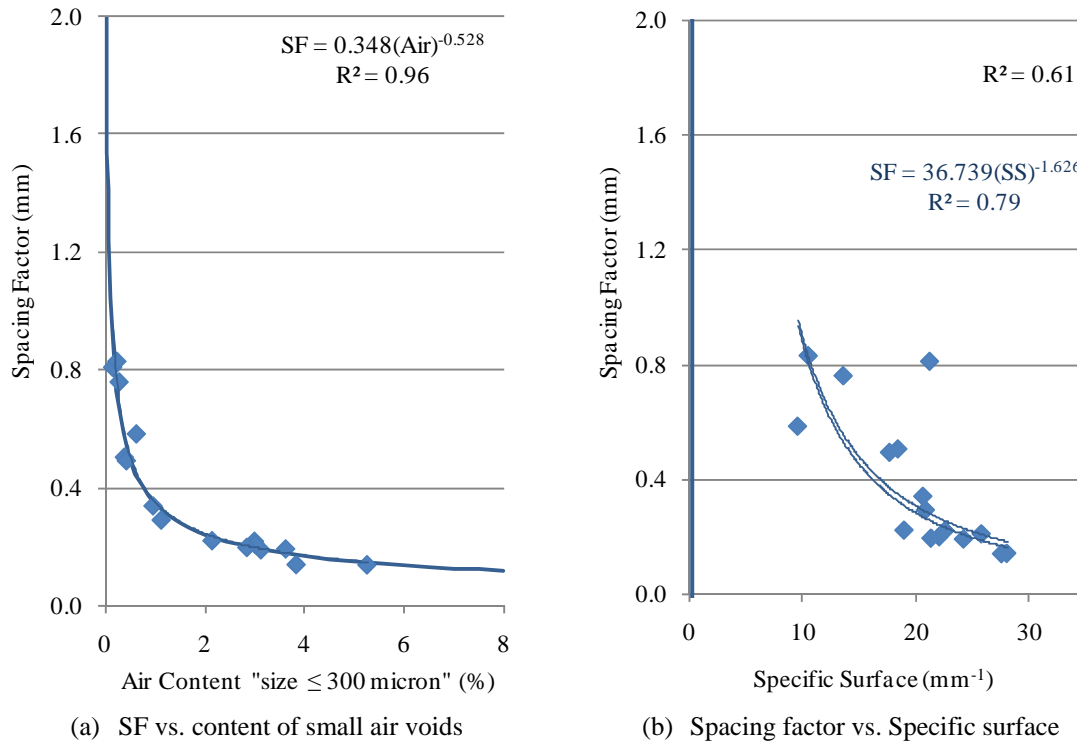
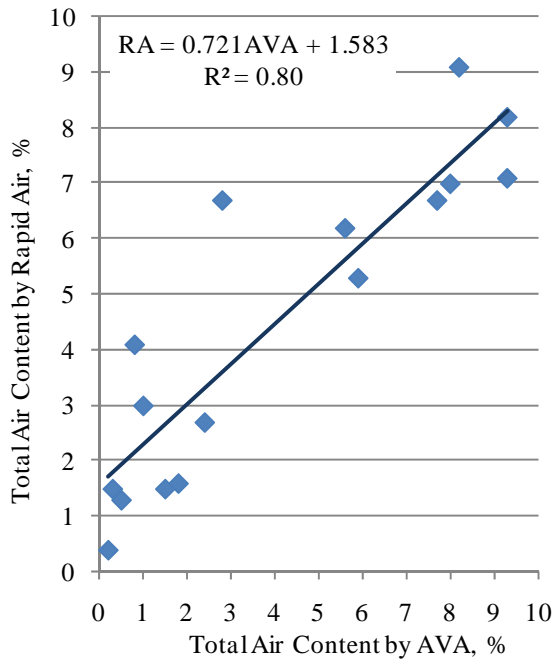
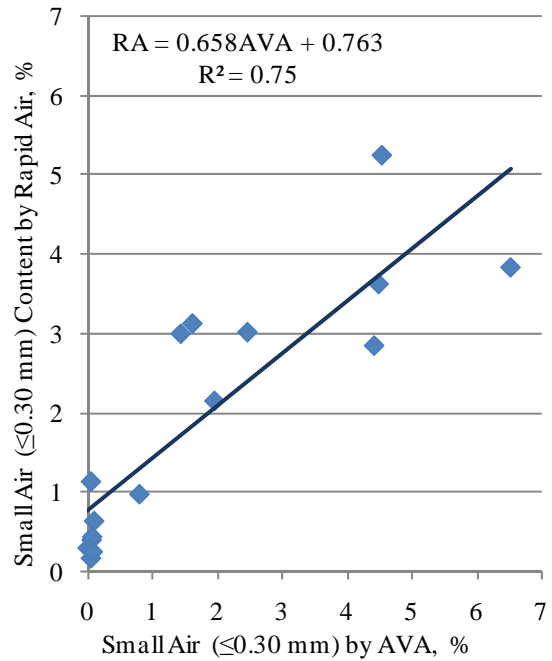


Figure 4.2. Relationships between air void parameters measured by Rapid Air

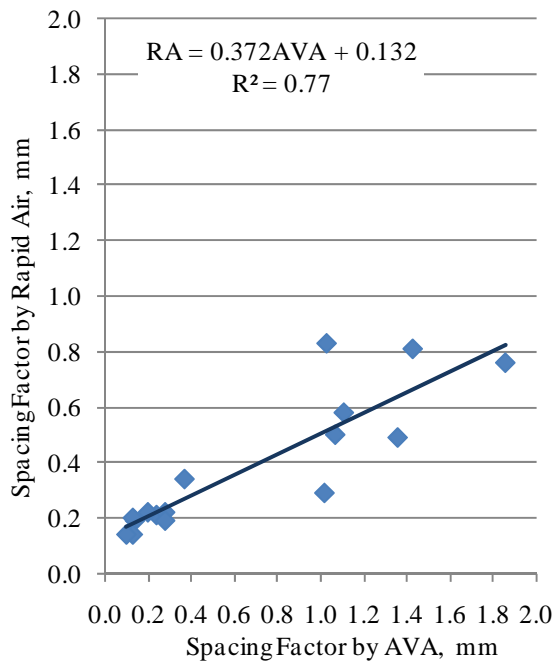
Figure 4.3 shows that certain relationships exist between RapidAir and AVA measurements. Based on the present test data, the total air content and specific surface measured by the RapidAir test method were noticeably higher than those values measured by the AVA test method. The small air contents measured by both test methods were comparable. The SF measured by the RapidAir test method was much lower than that measured by the AVA test method.



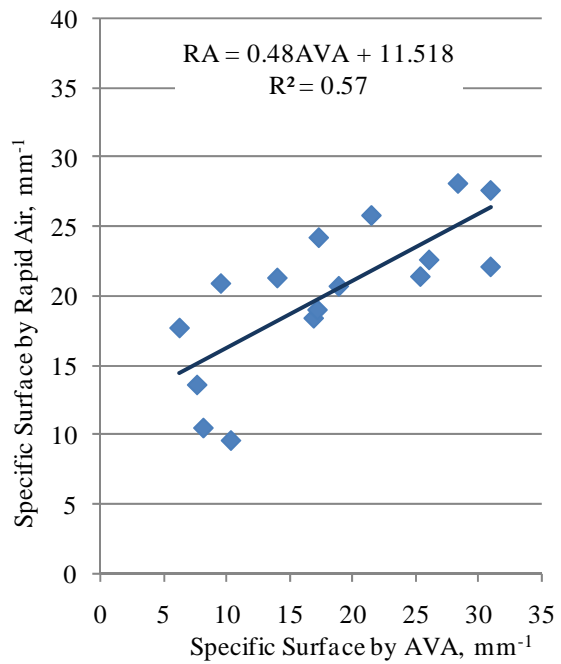
(a) Total air content



(b) Small air (≤0.3mm) content



(c) Spacing factor



(d) Specific surface

Figure 4.3. Relationships between RapidAir and AVA measurements

Figure 4.4 shows the correlation between the percent air obtained from RapidAir or AVA testing and the pressure method. The resulting trend lines show that the results from RapidAir and AVA testing are lower than the results obtained by C231, and the results from AVA testing are slightly lower than those from RapidAir.

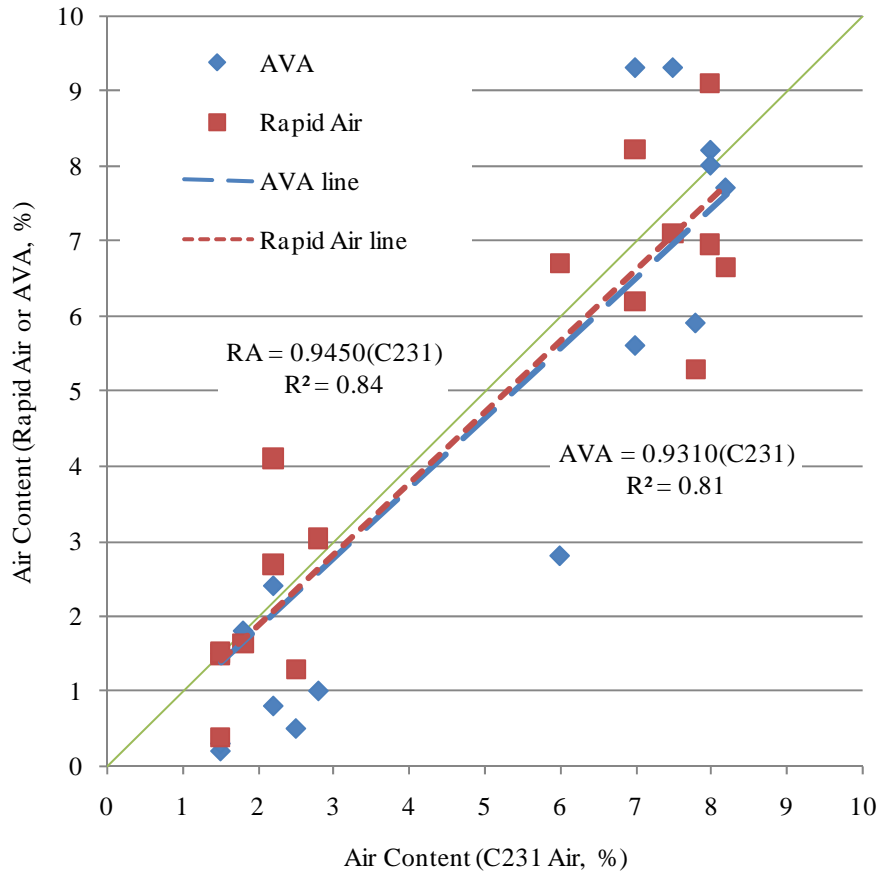
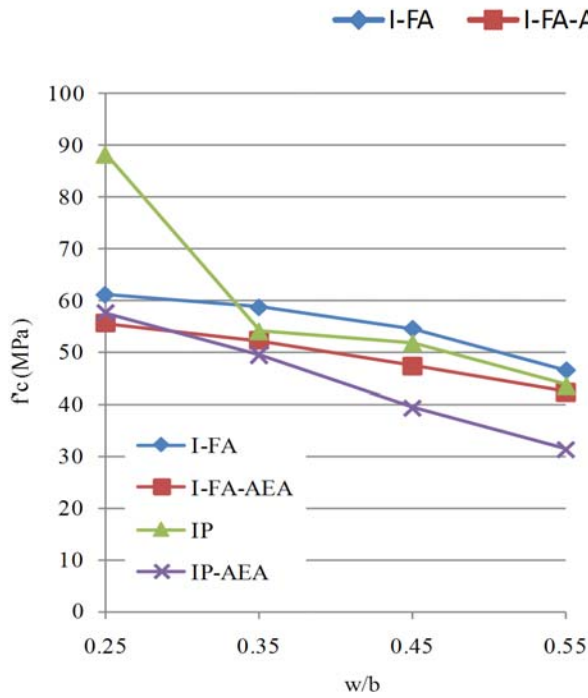


Figure 4.4. Correlation of results from RapidAir and AVA with ASTM C231

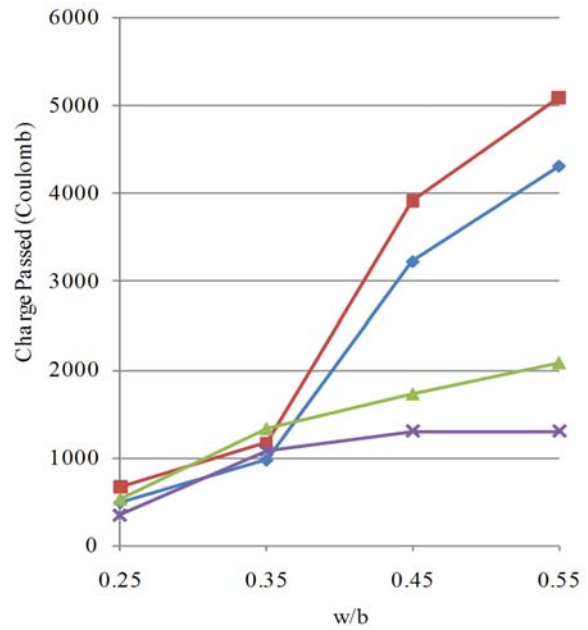
4.2 Relationship between Hardened Concrete Properties

Figure 4.5 illustrates the relationships between hardened concrete properties, including 28-day compressive strength, rapid chloride permeability, and porosity.

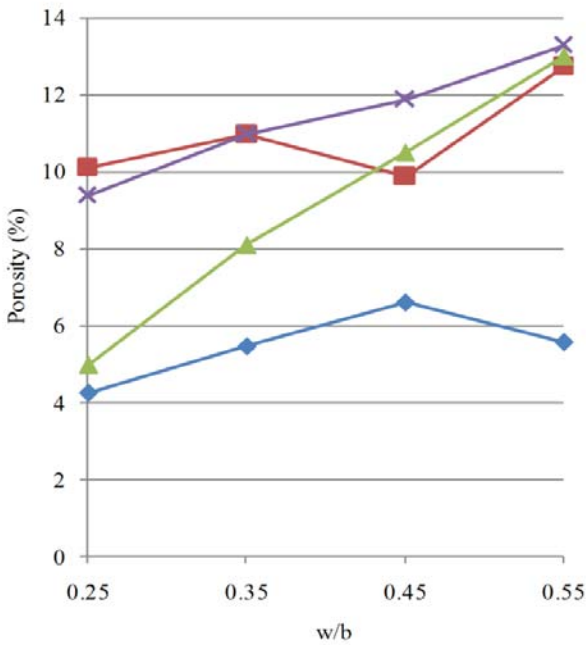
Figure 4.5 (a) to (c) shows that, with increasing w/b, concrete strength decreases while rapid chloride permeability and porosity increase. In the case of I-FA, when w/b becomes greater than 0.35, there is a more rapid increase in permeability. It can also be observed that concrete with AEA has a slightly lower strength but a much higher porosity than concrete without AEA.



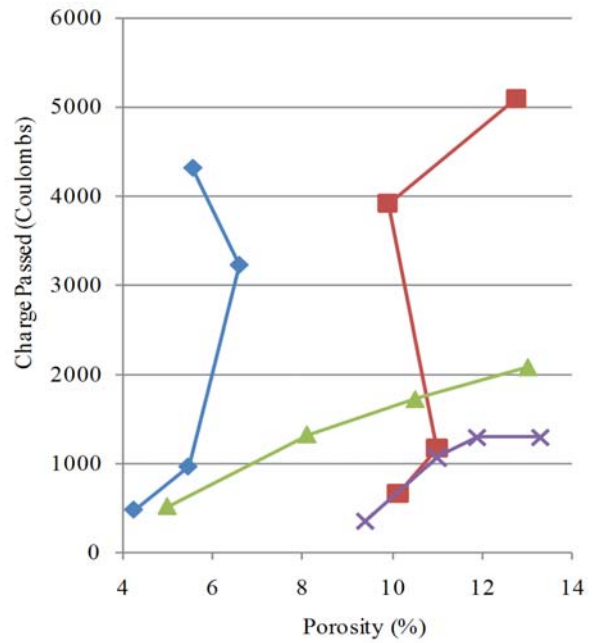
(a) Compressive strength vs. w/b



(b) Rapid Cl permeability vs. w/b



(c) Porosity vs. w/b



(d) Rapid Cl permeability vs. porosity

Figure 4.5. Relationship between hardened concrete properties

In Figure 4.5(d), the concrete with AEA has a much higher porosity than the concrete without AEA, whereas the difference in the permeability values of concrete with and without AEA is not as defined. For concrete with type IP cement, Figure 4.5(d) shows that there is an increase in

permeability with the increase in porosity, but for I-FA there is no clear relationship between concrete porosity and rapid chloride permeability.

It should be noted that, in addition to having the highest unit weight, concrete made with IP cement, a w/b of 0.25, no AEA (IP25) had the highest strength (88 MPa or 12,760 psi) and the lowest porosity (5%) among all mixes. Such properties significantly influence concrete F-T resistance.

4.3 Effects of Low-Permeability Concrete on F-T Durability

To investigate the effects on F-T durability of using low-permeability concrete made with either reduced w/b or SCMs, the durability factors were plotted as a function of porosity and rapid chloride ion permeability, as shown in Figure 4.6 and Figure 4.7, respectively.

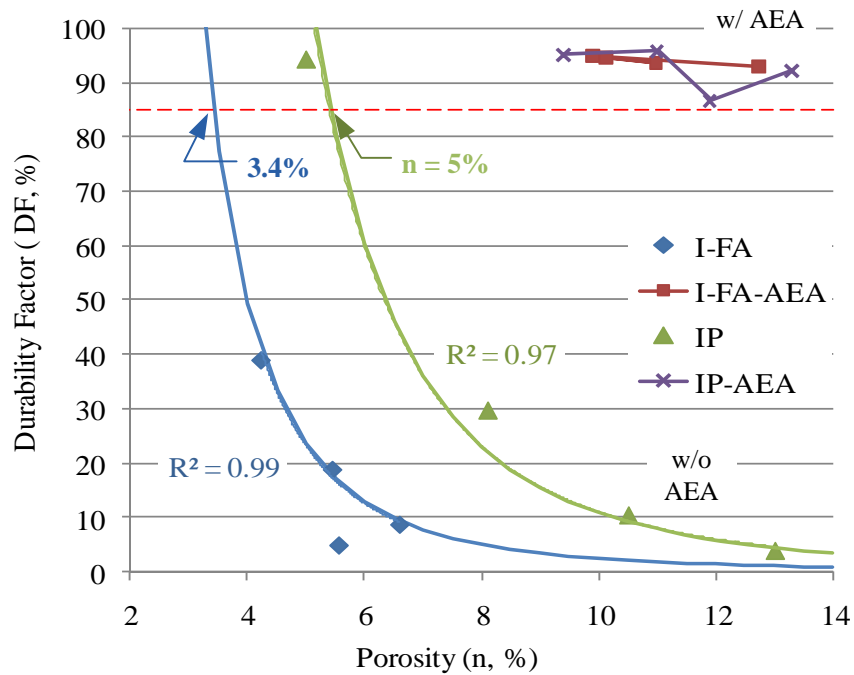


Figure 4.6. Durability factor as a function of porosity

For concrete without air entrainment, Figure 4.6 shows that durability increases with decreasing porosity. In terms of porosity, the concrete with Type I cement and Class C fly ash is less durable than concrete with Type IP due to the lower porosity required for I-FA to obtain the same durability. To have F-T durable concrete (durability factor $\geq 85\%$), IP should have a porosity of 5% or less, while I-FA should have 3.4% or less. These values were obtained using the following model equations:

$$DF_{I-FA} = 5158.9n^{-3.35} \quad \text{and} \quad DF_{IP} = 13120n^{-3.09} \quad (1)$$

Subscripts *I-FA* and *IP* denote the cementitious materials (Type I cement with 15% Class C fly ash and IP cement, respectively), and *n* is the porosity of concrete without AEA.

The trend line for I-FA does not include the results from I-FA55, as this data point is clearly an outlier. For the air entrained concrete samples, the relation between porosity and durability is not as well defined as the relationship for non-air entrained concrete samples. This is due to the role of the air void system in resisting F-T stresses. In this case, the samples may have high porosity values but still have high durability factors. The entrained air tends to increase porosity, but the air void system provides room for freezing water to expand and thus reduces stress.

As Figure 4.7 shows, the F-T durability of non-air entrained concrete can also be expressed as a function of rapid chloride ion permeability. As the chloride ion permeability decreases, the concrete durability increases. Also in this case, IP shows more durability with a higher permeability than does the I-FA. The range in which the durability factor remains above 85% is 608 Coulombs or less for IP and 185 Coulombs or less for I-FA. These values were obtained using the following model equations:

$$DF_{I-FA} = 7531.8k^{-0.86} \quad \text{and} \quad DF_{IP} = 4.0e7k^{-2.06} \quad (2)$$

where *k* is the rapid chloride permeability of concrete without AEA.

Similar to its relation to concrete porosity, chloride ion permeability does not seem to directly relate to F-T durability. Air entrained concrete may have a relatively high chloride ion permeability but maintain high F-T durability.

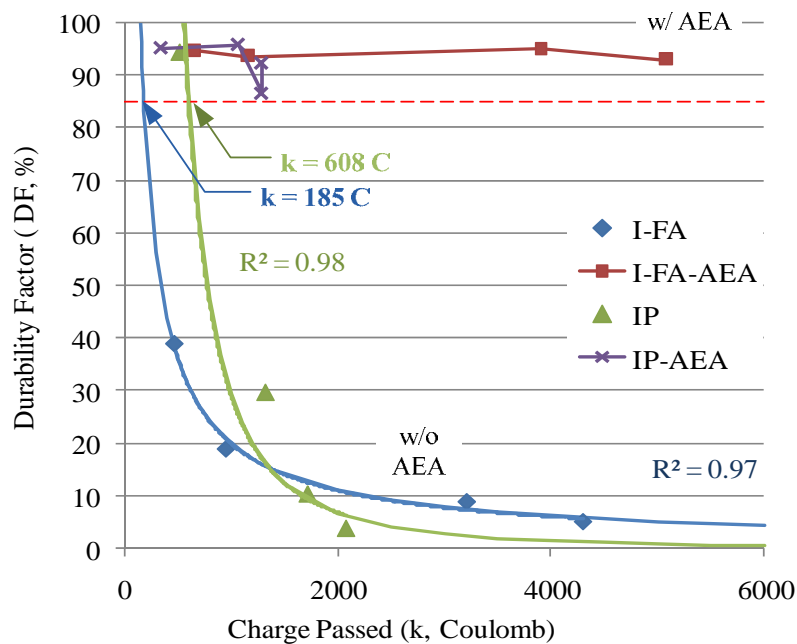


Figure 4.7. Durability factor as a function of rapid chloride ion permeability

4.4 Effects of w/b and Strength on F-T- Durability

Water in large enough capillary pores will freeze near or a few degrees below its normal freezing point (Philleo 1987). When the pores become smaller, the water in them tends to require much lower temperatures to freeze. For concrete without air entrainment for durability, freezable water must be eliminated. One of the ways that this may be achieved is to reduce the w/b to minimize the capillary pores. Reducing the w/b also has the benefit of lowering permeability (as shown in Figure 4.5(b)) and thus hindering water saturation in the concrete. The w/b can then be related to F-T durability. Figure 4.8 shows the concrete durability factor as a function of w/b. Similar to porosity and chloride ion permeability, the F-T durability of non-air entrained concrete increases as w/b decreases. For the samples tested, the relationships are expressed as follows:

$$DF_{I-FA} = 1.09(w/b)^{-2.62} \quad \text{and} \quad DF_{IP} = 0.48(w/b)^{-3.72} \quad (3)$$

To achieve a durability factor of 85% or greater, the limiting w/b of IP concrete without AEA is 0.26. For I-FA concrete, the limiting w/b is 0.19. It should be noted that the concrete samples were prepared in a laboratory and that the lowest w/b ratio for the tests was 0.25. The w/b of 0.19 was obtained by interpolating the results. In terms of current pavement construction practice, a w/b of 0.19 is not attainable in the field, while a w/b of 0.26 is not practical. Such a low w/b is especially not conducive for slip form paving.

The limiting w/b does not apply to air entrained concrete, because F-T durability would depend more on the concrete's entrained air system than on w/b. The w/b of I-FA55-AEA and I-FA25-AEA greatly differ, yet their durability factors are similar. The same is the case for IP55-AEA and IP25-AEA.

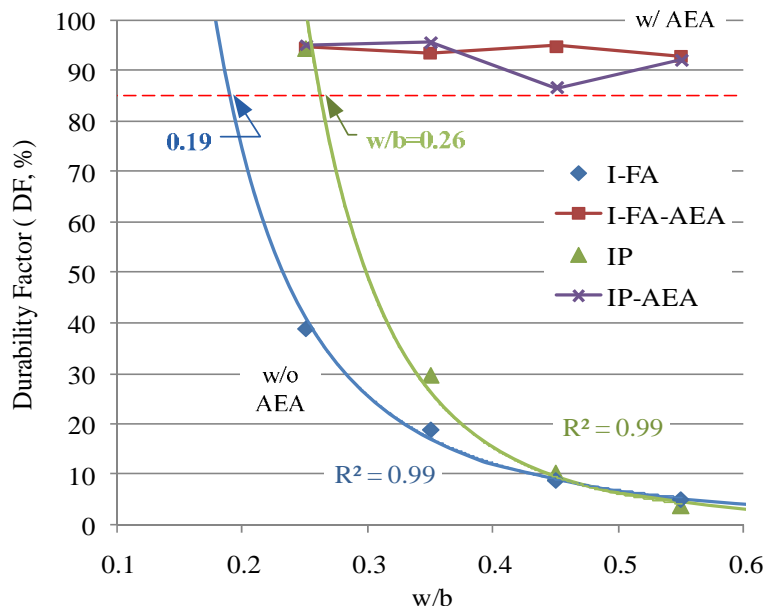


Figure 4.8. Durability factor as a function of w/b

In addition to w/b, the effect of strength on F-T durability was examined. Generally, concrete gets damaged because the stresses developed in the concrete are higher than the concrete strength. As a result, concrete F-T durability increases with strength. This concept is reflected in Figure 4.9 in the performance of the concrete without AEA. For concrete with AEA, the relationships between concrete durability factor and strength or w/b were not clear, even though the relationship between concrete strength and w/b held well.

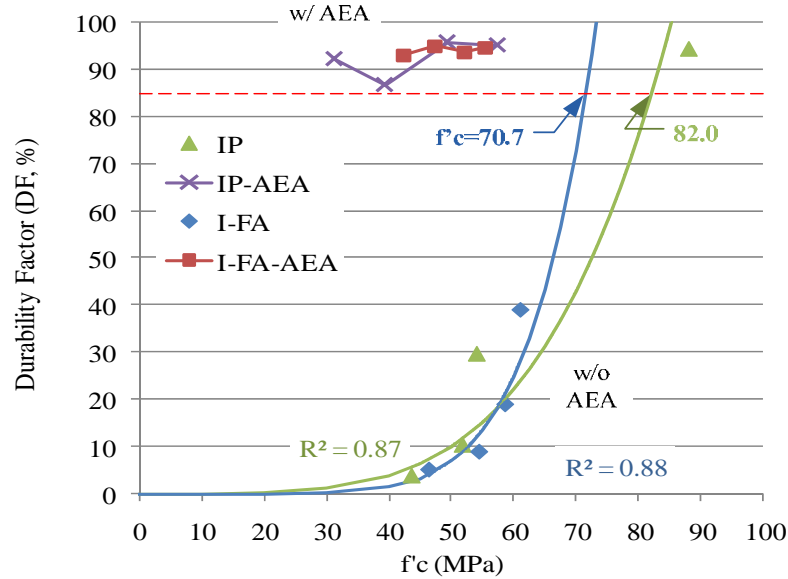


Figure 4.9. Durability factor as a function of strength

Based on the present study, the relationships between durability factor and 28-day compressive strength (f'_c) of non-air entrained concrete can be expressed by Equation (4):

$$DF_{I-FA} = 1.05e - 11(f'_c)^{6.96} \quad \text{and} \quad DF_{IP} = 5.24e - 7(f'_c)^{4.29} \quad (4)$$

According to Equation (4), concrete made with Type I cement and Class C fly ash requires a 28-day compressive strength of 70.7 MPa (10,246 psi) to be F-T durable (durability factor $\geq 85\%$). Concrete made with IP cement requires 28-day compressive strength of 82 MPa (11,880 psi).

In the study by Pigeon et al. (1991) on the F-T durability of high-strength concrete, the authors suggested that the w/b ratio below which air entrainment becomes unnecessary, for a concrete with Type I cement, 6% silica fume, and dolomitic limestone, is “probably” on the order of 0.25, which is a similar result range in the present study. It is also interesting to note that in the authors’ study, the 28-day compressive strength and SF are 11,930 psi and 0.69 mm, respectively. In the case of IP25, the compressive strength and spacing factor is 82.0 MPa (12,760 psi) and 0.83 mm, respectively.

In a study by Whiting (1987) on the durability of high-strength concrete, all moist-cured samples without air entrainment failed to reach 300 F-T cycles before having a relative dynamic modulus below 60%. The range of study for non-air entrained concrete included a w/b range of 0.31 to 0.56, and a 28-day compressive strength range of 10,000 to 6,000 psi. Consistent with the present study, these values are not within the range found that would provide sufficient F-T durability for concrete without air entrainment.

4.5 Effects of Cement Type on the Effectiveness of Air Entrainment

The effectiveness of air entrainment was evaluated in this study by comparing the concrete’s durability factor after 300 F-T cycles to the amount of and spacing factor for the entrained air. The parameters used for evaluating air entrainment in concrete include air content greater than 6% and spacing factor 0.2 mm or less. The air entrainment is considered effective if the durability factor is $\geq 85\%$. Figure 4.10 to Figure 4.12 show the relationship between the durability factor and the amount of air and spacing factor of the air entrained samples. (The “AEA” was dropped in the figures to reduce the labels’ sizes.) There are eight cases of air entrained concrete in this study, including four w/b ratios for each type of cementitious material. The result for each case is the average of three samples.

For samples with AEA, Figure 4.10 shows the relationship between durability factor and the percentage of air obtained from the ASTM C231 pressure method. The figure shows that for all cases, when the amount of air is above 6%, the durability factor is also above 85%.

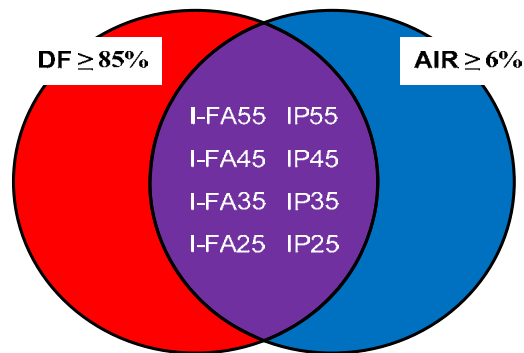


Figure 4.10. Relationship between durability factor and % air, by ASTM 231, of air entrained samples

For the results obtained from the air entrained concrete samples using the AVA, Figure 4.11 shows the relationship between the durability factor and the amount of air and spacing factor. The results show that 100% of the samples that meet the required amount of air and the required spacing factor have durability factors greater than 85%. I-FA55-AEA has good durability because its air content (5.9%) is very close to the required. IP35-AEA also has a high durability factor because its air content (5.6%) is close to the required and because its spacing factor is small (0.28 mm). IP55-AEA does not meet either the air or spacing factor criteria but still has good durability. This is because its spacing factor is still small (0.28 mm) and, considering Figure 4.10, because IP55-AEA shows sufficient air entrainment to provide good durability.

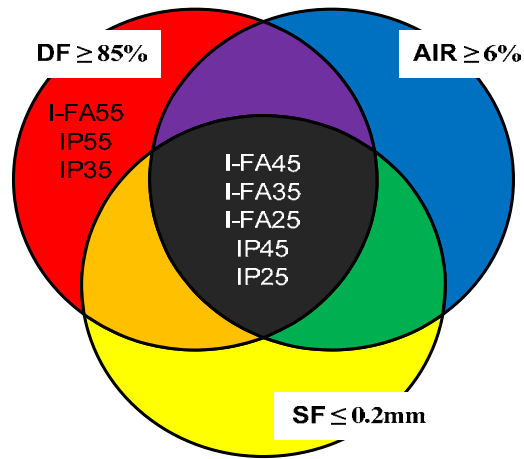


Figure 4.11. Relationship between durability factor and % air and spacing factor of air entrained samples, obtained by AVA

For the results obtained from the RapidAir equipment, Figure 4.12 shows the relationship between the durability factor and the air structure. In this case, 100% of the samples that meet the air structure requirement also have a durability factor greater than 85%. I-FA55-AEA has a durability factor greater than 85% because its air content (5.3%) and spacing factor (0.21 mm) are close to the required. In the case of I-FA25-AEA and IP55-AEA, their spacing factors are both 0.22 mm, close enough to 0.2 mm to provide good F-T durability.

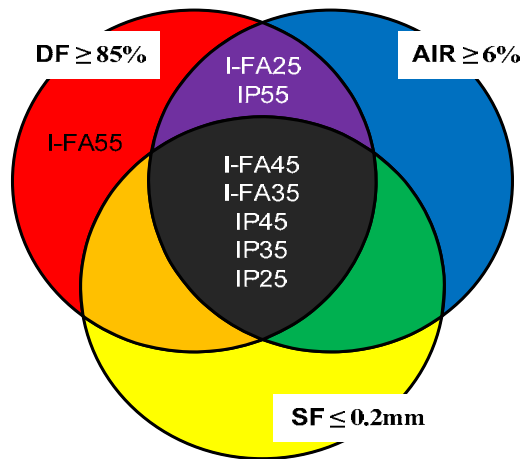


Figure 4.12. Relationship between durability factor and % air and spacing factor of air entrained samples, obtained by RapidAir

Based on the results obtained, the effectiveness of air entrainment in terms of resistance to F-T damage depends largely on the amount and structure of the entrained air and is not affected by the type of cementitious material. When the air structure is sufficient, then a good F-T durability can be obtained.

4.6 Interaction between Cementitious Materials and AEA

The interaction between the cementitious materials and AEA is based on the amount of air entrained for the same admixture and dosage. As described above, the cementitious materials included I-FA (a combination of Type I cement and Class C fly ash) and IP (Type IP, blended Type I and Class F fly ash cement), and the AEA was an aqueous solution compound of synthetic organic chemicals. The amount of AEA required to have sufficient air entrainment varies depending on type of cement, fineness of sand, temperature, design of the mix, etc. For this study, the amount of admixture was varied to achieve sufficient air entrainment.

The results from the I-FA mixtures showed that sufficient air entrainment can be achieved with the same dosage of admixture. The amount of air measured using the pressure method ranged from 7% to 8.2%. With the AVA, the entrained air varied from 5.9% to 9.3%, while the results measured with the RapidAir equipment varied from 5.3% to 8.2%. Because the tests are taken from different conditions of the sample (i.e., the pressure method uses rodded plastic concrete, the AVA uses vibrated mortar, the RapidAir uses hardened concrete), the fact that the entrained air remained above 5% means that it may be considered stable.

The IP mixtures have a less stable air entrainment. The amount of air measured with the pressure method ranged from 6% to 8%, while the amount of air measured with the AVA and RapidAir, respectively, ranged from 2.8% to 9.3% and from 6.24% to 9.1%. To achieve these amounts of air entrainment, the dosage of AEA had to be increased with a decreasing w/b and an increasing amount of cementitious material.

4.7 Effect of Air Void Structure on F-T Durability

Figure 4.13 shows that, for this study, all of the samples with air contents $\geq 6\%$ had good F-T durability (durability factor $\geq 85\%$). For the samples without AEA, all except one of the samples with air contents less than 6% had poor F-T durability. The exception to these criteria was IP25, which has a low air content and high durability. This mixture showed a very high compressive strength (12,760 psi) and a low porosity (5%) and permeability (350 C).

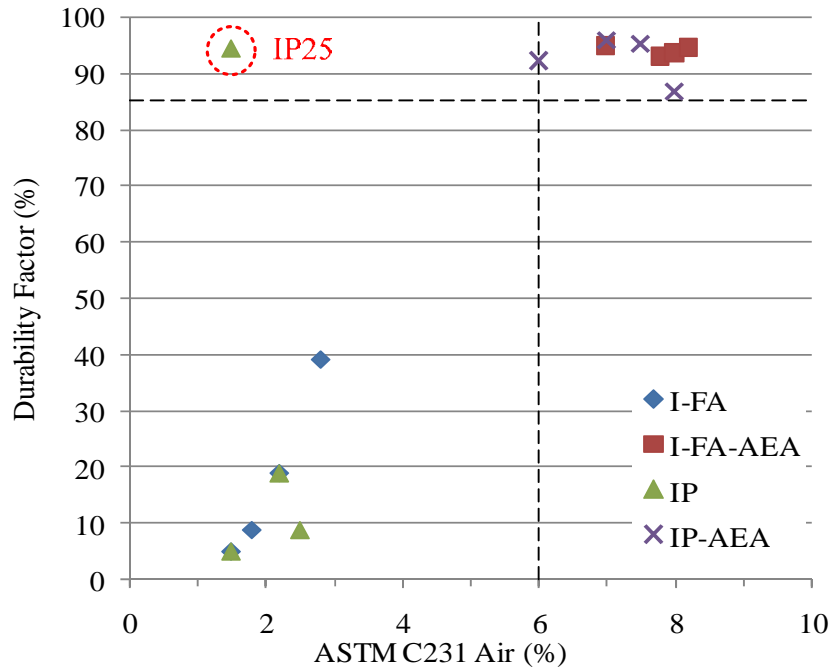


Figure 4.13. Durability factor as a function of the amount of air, measured following ASTM C231

A spacing factor criterion of ≤ 0.20 mm is usually adopted to determine an adequate F-T durability for concrete. In the present study, it is shown in Figure 4.14 that all samples having a spacing factor of ≤ 0.28 mm and less are F-T durable. Samples with a higher spacing factor were not F-T durable, except for IP25, which had a SF of 1.03 mm.

For the spacing factor as measured by RapidAir, shown in Figure 4.15, all samples having a spacing factor of ≤ 0.28 mm and less are F-T durable. Samples with a higher spacing factor were not F-T durable, except for IP25, which had a SF of 0.83 mm.

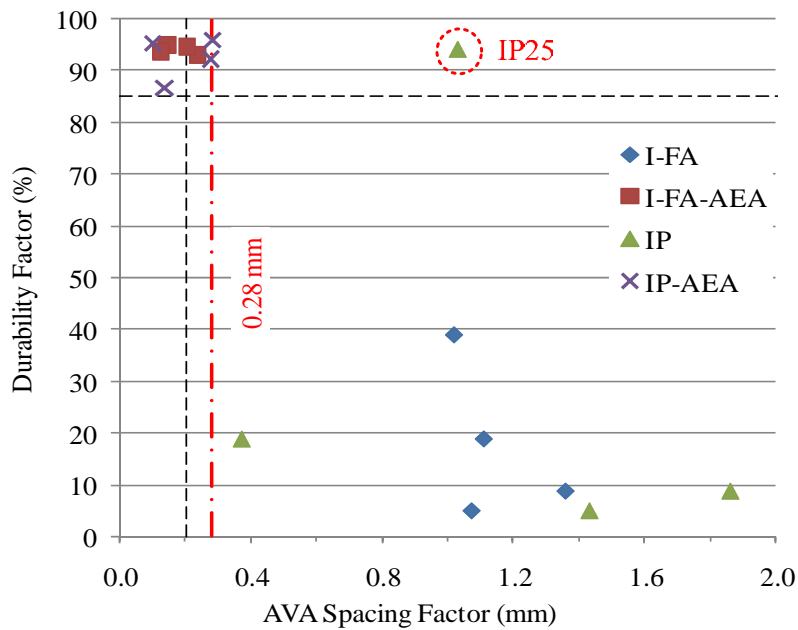


Figure 4.14. Durability factor as a function of spacing factor, measured using the AVA

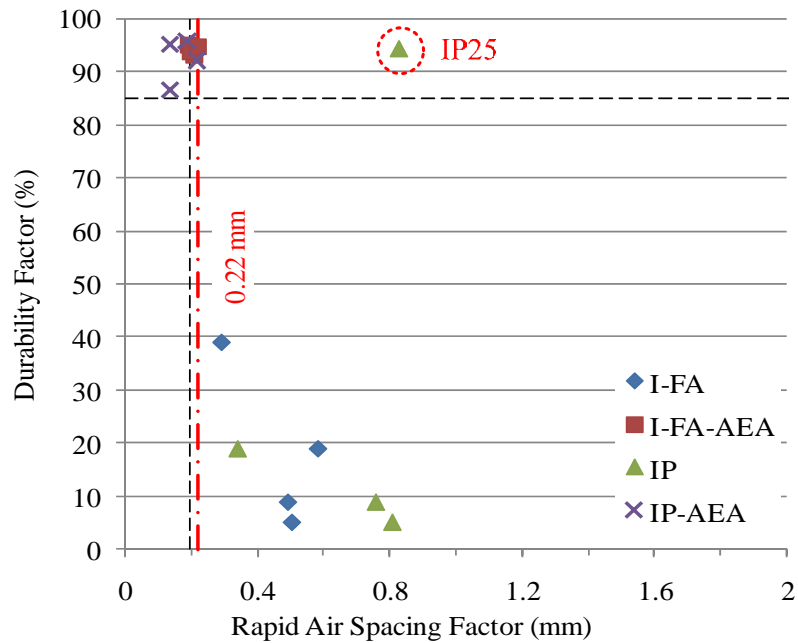


Figure 4.15. Durability factor as a function of spacing factor, measured using the RapidAir

Pigeon et al. (1991) studied the F-T durability of high-strength concrete and suggested that the limiting w/b, below which air entrainment is not required for concrete made with Type I cement, 6% silica fume, and dolomitic limestone, is “probably” on the order of 0.25, which is a similar result range in the present study. It is also interesting to note that, in the Pigeon et al. study, the 28-day compressive strength and spacing factor for F-T durable concrete was 82.3 MPa (11,930

psi) and 0.69 mm, respectively. In the present study, the only F-T durable concrete mix without AEA was mix IP25, which had a compressive strength of 88.0 MPa (12,760 psi) and a spacing factor of 0.83 mm (measured by RapidAir).

In addition, the results from the present study are consistent with those from previous research, although different test methods for concrete air void structure analysis were applied. Whiting (1987) studied the F-T durability of high-strength concrete and reported that all moist-cured samples without air entrainment failed with a dynamic modulus below 60% before reaching 300 F-T cycles. The concrete in that study had no AEA, a w/b ranging from 0.31 to 0.56, and a 28-day compressive strength between 6,000 and 10,000 psi.

5. CONCLUSIONS

The F-T durability of concrete without air entrainment increases as rapid chloride permeability decreases and strength increases. Low-permeability concrete without air entrainment can be F-T durable if the concrete also has very high strength. In the present study, the concrete mix made with Type IP cement and without AEA had a durability factor of 94.3%, along with a rapid chloride permeability of 520 coulombs and a 28-day compressive strength of 88.0 MPa (12,760 psi).

For concrete with AEA, the effectiveness of air entrainment for resisting F-T deterioration is dependent mostly on the air void system rather than the type of cementitious material. To ensure F-T durability, according to the tests conducted, the amount of air needed to be 6% or greater (measured with ASTM C231) and the spacing factor needed to be 0.28 mm or less when measured using AVA or 0.22 mm or less when measured using RapidAir.

The relationships between concrete F-T durability and other properties (such as rapid chloride permeability, porosity, and w/b) have been clearly demonstrated by the concrete made with given cementitious materials and without AEA. These relationships can be expressed as a power form: $DF = a \cdot (P)^{-b}$, where a and b are constant and P is the above-mentioned concrete properties. These relationships do not exist for the concrete with AEA.

6. RECOMMENDATIONS

It is quite common, even for high-performance concrete, to have air entrainment when the concrete's application involves freezing and thawing conditions. In a publication of the Portland Cement Association (PCA), Kosmatka (2006) mentioned that air entrainment is mandatory for high-strength concrete, but the author recognizes that the amount of air entrainment may be reduced. The author also notes applications where good freeze-thaw resistance is obtained for high-strength concrete without air entrainment.

Based on the present findings, low permeability alone would not guarantee F-T durability. Rather, it is the combination of low permeability and high strength that would make concrete F-T durable without air entrainment. It has been noted in Section 4.4 that very low w/b (0.19 and 0.26) either cannot be achieved in the field or is impractical. However, if casting conditions would permit, low permeability can be attained with the following:

1. Using supplementary cementitious materials, such as fly ash, slag, metakaolin, or silica fume
2. Increasing the degree of hydration by longer moist-curing periods
3. Using a lower water-to-cement ratio

The above factors are also responsible for increasing concrete strength. Additionally, one must carefully consider aggregate properties and gradation.

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APPENDIX A. IMAGES OF BEAM SAMPLES AFTER F-T TEST



I-FA55



I-FA45



I-FA35



I-FA25

Figure A.1. I-FA beams after F-T cycles



I-FA55-AEA



I-FA45-AEA



I-FA35-AEA



I-FA25-AEA

Figure A.2. I-FA-AEA beams after F-T cycles



IP55



IP45



IP35



IP25

Figure A.3. IP beams after F-T cycles



IP55-AEA



IP45-AEA



IP35-AEA



IP25-AEA

Figure A.4. IP-AEA beams after F-T cycles