Two points are worthy of note:

1. The addition of 89 kg/m^3 of fly ash F2 to the silica fume mixture significantly improved the strength and impermeability of concrete when compared with the mixture containing portland cement and silica fume only.

2. At 56 days, fly ash F2 at 119 and 178 kg/m^3 exhibited higher compressive strengths and lower permeabilities than the mixtures containing a 10% silica fume addition at a portland cement content 45 kg/m^3 lower for the fly ash mixes.

Low permeability was recorded for the 50% GGBFS concrete mixtures despite a relatively high water/cementitious materials ratio.

The concretes produced in this study were selected as examples of relatively high quality, low water/cementitious material ratio concretes (such as might be specified in areas of extreme exposure conditions) with a variety of cementing materials, to provide information on the reduced permeability of concretes containing these materials. The test results show that when fly ash, silica fume, and GGBFS are used in concretes in proper proportions with superplasticizers, permeability results achieved rated "Very Low" to almost "Negligible" in the Chloride Ion Permeability Rating established in AASHTO T-277.

The work in this study is not exhaustive, but indicates that the low levels of chloride permeability in concrete that have been achieved by using silica fume can also be obtained by using fly ash appropriately. As an example, research has shown that the <u>addition</u> of fly ash as a replacement for a portion of the aggregate in concrete reduced the corrosion rates of reinforcing bars very significantly, compared with mixes containing portland cement only, in a chloride environment(6).

The results presented here would further highlight the benefit of the consideration of the cementitious materials studied as discrete ingredients for producing concrete with the specified engineering properties, by utilizing the appropriate amounts of selected ingredients to produce the desired result. Blends of cementitious materials can thus be designed for any desired compressive strength level to meet specific durability requirements as well. As has been well documented (Mehta has authored an excellent overview of the state of current technology.(7)), obvious design criteria which may be singly or simultaneously achieved through judicious proportioning of concrete mixtures using fly ash, silica fume, and GGBFS include:

1. Fresh concrete properties

2 Heat of hydration control

3. Concrete strength at any age

4. Durability parameters such as permeability, control of alkali-silica reaction, resistance to sulfate- and chloride-rich environments, and freeze thaw resistance(8)

5. Economy depending on the pricing of the various cementitious materials

The simplistic "replacement" theories must be discarded in favor of more realistic mixture proportioning criteria which acknowledge that the inclusion of larger quantities of fly ash, GGBFS, and silica fume are not detrimental, but desireable in the production of more durable concrete.

CONCLUSIONS AND COMMENTARY

The results of the experimental work presented herein support the blending of portland cement with appropriate quantities of fly ash, totally independent of any arbitrary "replacement levels", to produce concretes which are superior in reducing the chloride permeability of concrete to those containing portland cement only. Of further interest are the comparison with silica fume and GGBFS used in mixes at normal commercial levels, and the effect of the addition of fly ash to a silica fume mixture.

The results of this study demonstrate that increasing the amount of fly ash in concrete at a constant cement factor can reduce the chloride permeability of the concrete, as well as increase the 28- and 56-day compressive strengths.

Class F fly ashes showed very significant improvements over portland cement control mixes, in reducing chloride permeability and gave results comparable or superior to those achieved using silica fume or GGBFS. The phenomenon is verified in research by Sivasundaram, et al in work conducted with high volume fly ash concretes.(9) The chloride permeability of concretes containing Class C fly ash were not as good as those containing Class F at the same inclusion rate, but were improved over portland cement only, at comparable cementitious contents.

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REFERENCES

1. Li, Shiqun and Della M. Roy, "Investigation of Relations Between Porosity, Pore Structure, and Cl^- Diffusion of Fly Ash and Blended Cement Pastes", Cement and Concrete Research, Vol. 16, No. 5, 1986, pp. 749-759,

2. Li, Shiqun and Della M. Roy, "Investigation of Relations Between Porosity, Pore Structure, and Cl^- Diffusion of Fly Ash and Blended Cement Pastes", Cement and Concrete Research, Vol. 16, No. 5, 1986, pp. 749-759,

3. Dhir, Ravindra K, "Pulverized Fuel Ash", Cement Replacement Materials, Surrey University Press, Glasgow, 1986, pp. 220-244 (ed. Swamy, R.N.).

4. Butler, W. Barry, "Economical Binder Proportioning with Cement-Replacement Materials", Cement, Concrete, and Aggregates, Vol. 10, No. 1., American Society for Testing and Materials, pp. 45-47.

5. Majko, Richard M. and Michael F. Pistilli, "Optimizing the Amount of Class C Fly Ash in Concrete Mixtures", Cement, Concrete, and Aggregates, Vol. 6, No. 2., American Society for Testing and Materials, pp. 105-119.

6. Maslehudden, Mohammed, Abdulaziz I. Al-Mana, Mohammed Shamim, and Huseyin Saricimen, "Effect of Sand Replacement on the Early Age Strength Gain and Long - Term Corrosion - Resisting Characteristics of Fly Ash Concrete", ACI Materials Journal, American Concrete Institute, January-February, 1989, pp. 58-62.

7. Mehta, P.K., " Pozzolanic and Cementitious By-Products in Concrete - Another Look", SP 114, American Concrete Institute, 1989, pp. 1-43.

8. Drahushak-Crow, Roselle, "Freeze-Thaw Durability of Fly Ash Concrete", EPRI Proceedings: Eighth International Ash Utilization Symposium-colume 2, October, 1987, p. 37-1

9. Sivasundaram, V., G.G. Carette, and V.M. Malhotra, "Properties of Concrete Incorporating Low Quantity of Cement and High Volumes of Low-Calcium Fly Ash", SP 114, American Concrete Institute, 1989, pp. 45-71.

TABLE 1

CHEMICAL AND PHYSICAL PROPERTIES OF CEMENTITIOUS MATERIALS USED

Chemical Composition (%)	Portland Cement	Fly Ashes			Silica Fume (Typical)	GGBFS (Typical)
		F1	F2	C		
CaO	65.8	1.8	10.2	28.3	0.5	38.6
SiO_2	22.0	53.2	56.3	34.6	96	35.3
Al_2O_3	4.1	30.6	23.8	19.5	0.1	11.1
Fe_2O_3	3.1	7.5	3.9	6.8	0.03	0.9
MgO	0.9	0.8	2.1	4.5	1.1	12.9
SO_3	2.7	0.1	0.3	0.8	-	-
S	-	-	-	-	0.2	1.1
LOI	0.9	1.3	0.3	0.4	2.5	-
Alkalis (eq. Na_2O)	-	0.5	0.3	1.5	0.04	-
% retained on 45 um sieve	-	23.2	19.5	18.6	-	-
Fineness (cm^2/cm^3)	10,400[1]	12,600[2]	18,400[2]	20,300[2]	200,000[3] cm^2/g	16,200[1]
Specific gravity	3.15	2.27	2.27	2.70	2.23	2.95
Potential compounds						
C_3S	61.0					
C_2S	17.1					
C_3A	5.6					
C_4AF	9.4					

1. Blaine
2. Cilas Granulometer 715
3. BET

TABLE 2	BATCH WEIGHTS, kg/m^3								CONCRETE PROPERTIES				
Mix #	Portland Cement	Fly Ash			Silica Fume	GGBFS	Coarse Aggregate	Fine Aggregate	Slump (mm)	w/c*	Compressive Strength (MPa)		Chloride perm.** 56 days (coulombs)
		F1	F2	C							28 day	56 day	
1	356	0	0	0	0	0	1003	986	95	0.35	52.9	58.8	2205
2	297	0	0	0	0	0	1003	1005	100	0.43	44.1	49.0	2882
3	252	59	0	0	0	0	1003	1010	75	0.37	52.5	58.9	890
4	252	119	0	0	0	0	1003	950	115	0.30	49.5	59.7	588
5	252	178	0	0	0	0	1003	832	125	0.30	55.6	63.2	623
6	252	0	59	0	0	0	1003	1019	90	0.35	46.0	52.5	1184
7	252	0	119	0	0	0	1003	959	125	0.29	62.2	70.1	298
8	252	0	178	0	0	0	1003	820	115	0.31	74.9	82.3	169
9	252	0	0	59	0	0	1003	984	75	0.41	50.5	53.0	2490
10	252	0	0	119	0	0	1003	965	100	0.30	69.8	75.9	981
11	297	0	0	0	30	0	1003	975	90	0.39	66.6	68.8	408
12	297	0	89	0	30	0	1003	883	125	0.29	80.8	83.8	171
13	148	0	0	0	0	148	1003	987	125	0.47	49.6	55.7	662
14	356	119	0	0	0	0	1003	806	125	0.28	59.4	67.5	693
15	178	178	0	0	0	0	1003	918	100	0.33	40.2	47.5	756

*w/c is water cementitious ratio **Average of two specimens

All mixes contain ASTM C-494 Type F Superplasticizer at 780mL/kg of cementitious material

Figure 1

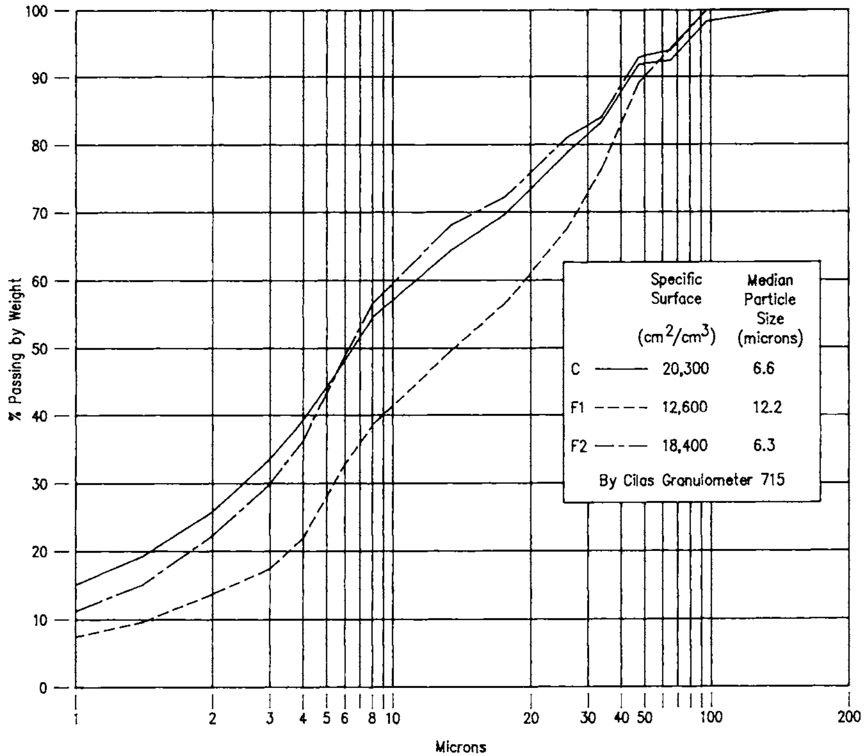
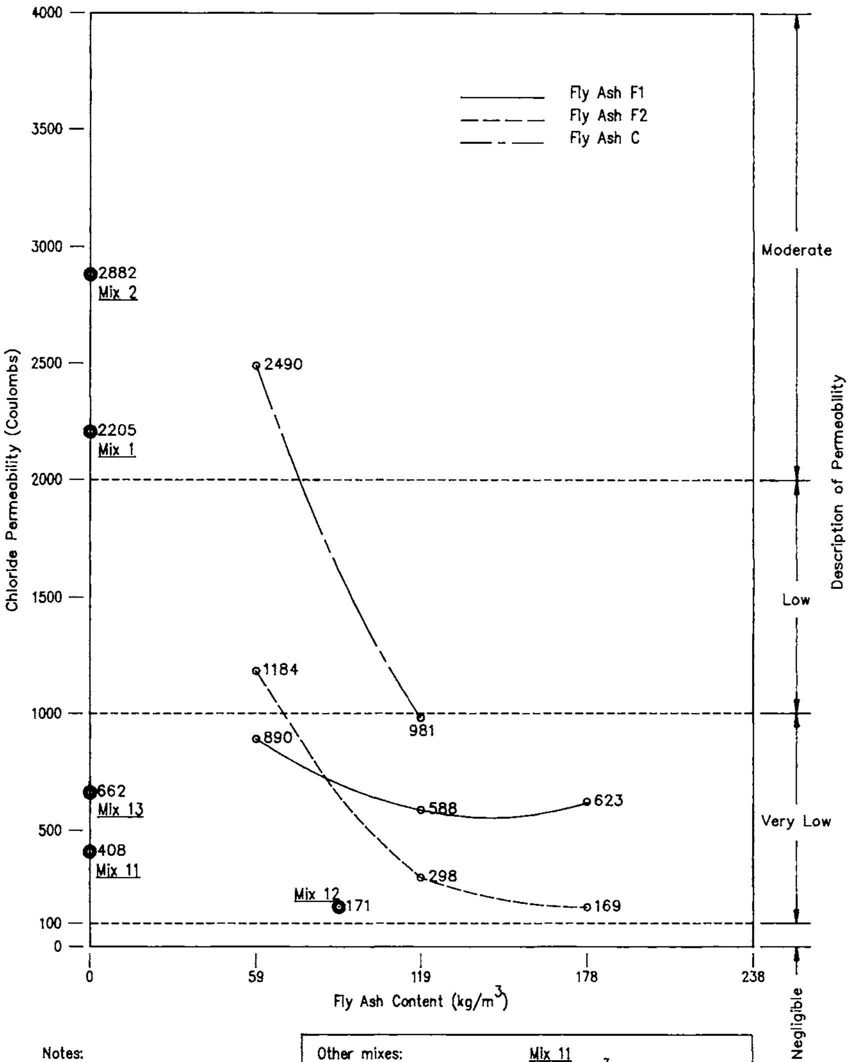


Fig. 1--Particle size distribution of fly ashes

Figure 2



Notes:
1. 28 day standard moist cure + 28 day lab air cure.
2. All fly ash mixes contain 252 kg/m^3 cement.
3. All mixes contain ASTM C494 Type F superplasticizer ● 780 mL/100 kg cementitious material.

Other mixes:

Mix 2
297 kg/m^3 Portland Cement

Mix 1
356 kg/m^3 Portland Cement

Mix 13
148 kg/m^3 Portland Cement + 148 kg/m^3 GGBFS

Mix 11
297 kg/m^3 Portland Cement + 30 kg/m^3 silica fume

Mix 12
297 kg/m^3 Portland Cement + 89 kg/m^3 Fly Ash F2 + 30 kg/m^3 silica fume

Fig. 2--Chloride permeability of concrete by AASHTO standard method of test T-277