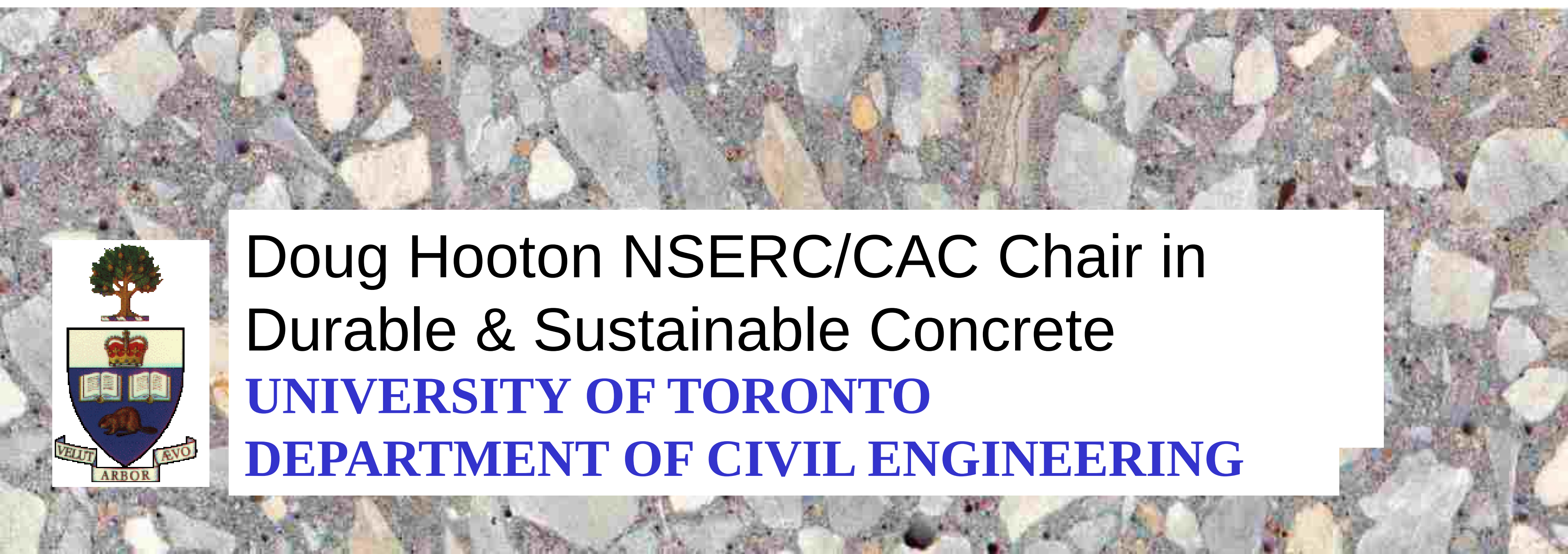
Advantages of Slag-Silica Fume Ternary Binders for Production of Durable Concrete



Doug Hooton NSERC/CAC Chair in Durable & Sustainable Concrete
UNIVERSITY OF TORONTO
DEPARTMENT OF CIVIL ENGINEERING


GGBF slag
grade 120
Si Silica Fume
(microsilica)
Portland Cement
Type I
Fly Ash
class C

General Advantages of SCM's

The advantages of properly designed and cured concretes containing SCM's are that lower permeability and chloride diffusion can be achieved :

1. There is more C-S-H formed which uses up $Ca(OH)_2$ and fills more space.
2. The reactions happen later, so that the new C-S-H subdivides and blocks the initial capillary pore system.
3. The porous aggregate transition zones (ITZ) become filled with C-S-H, reducing their influence.

General Advantages of SCM's

4. With SCMs, the C-S-H which forms has lower Ca/Si. To make up for this, the C-S-H incorporates more alkalies (substituting for Ca). This reduces the alkalinity of the pore solution, making it less likely to attack reactive aggregates.

5. SCM's with higher Al_2O_3 contents will also form C-A-S-H, (Al_2O_3 substituting for SiO_2) and other aluminate hydrates which will bind more chlorides and alkali.

Concerns with SCMs

- Often the initial rate of reaction is slower, especially at high replacement levels and at lower temperatures.
- This can be overcome by re-designing mixes to get early age properties, or by use of ternary mixtures—eg. Silica fume with slag or ash; or slag mixed with high-alkali Class C fly ash.
- Rates of reaction increase with increasing temperature, so replacement levels often have to change with seasons.

Slag and Silica Fume Use in Ontario, Canada

- Ground Granulated Blast-Furnace Slag has been produced since 1976 and is used by most concrete producers.
- Silica Fume has been available since 1978 and Type GUb8SF blended cement since 1982.
- Slag-Silica Fume Ternary systems have been used since 1986 and are commonly whenever Silica Fume is used.

Slag Uses and Concerns

- Typically 25% cement replacement is used for general purpose use in concrete and also in ternary systems with silica fume.
- Slag can also provide improved resistance to chlorides, sulfates, and ASR when used at replacement levels of 35 to 50%.
- However, setting times and early age properties may be retarded at high replacement levels or in cold weather.

SF Blended Cement

- Type Gub-8SF cement typically contains 7 to 9% Silica Fume (±0.5%)
- Makes SF easier to transport
- This reduces SF handling problems at the concrete plant
- This makes SF easier to disperse in concrete

Concerns with Silica Fume

- Silica Fume is often specified for High Strength or High Performance Concrete but requires high-dose rates of HRWR.
- Construction concerns have included finishing problems and plastic cracking.
- Strength development is fast but not much beyond 28 days.

Ternary Systems vs Silica Fume

Early-age advantages:

- Lower HRWR doses needed
- Easier to place
- Less “sticky” to finish
- Fewer contractor complaints
- Good early age properties (strength and chloride resistance) due to SF, and continued later-age improvement due to Slag
- Lower heat rise

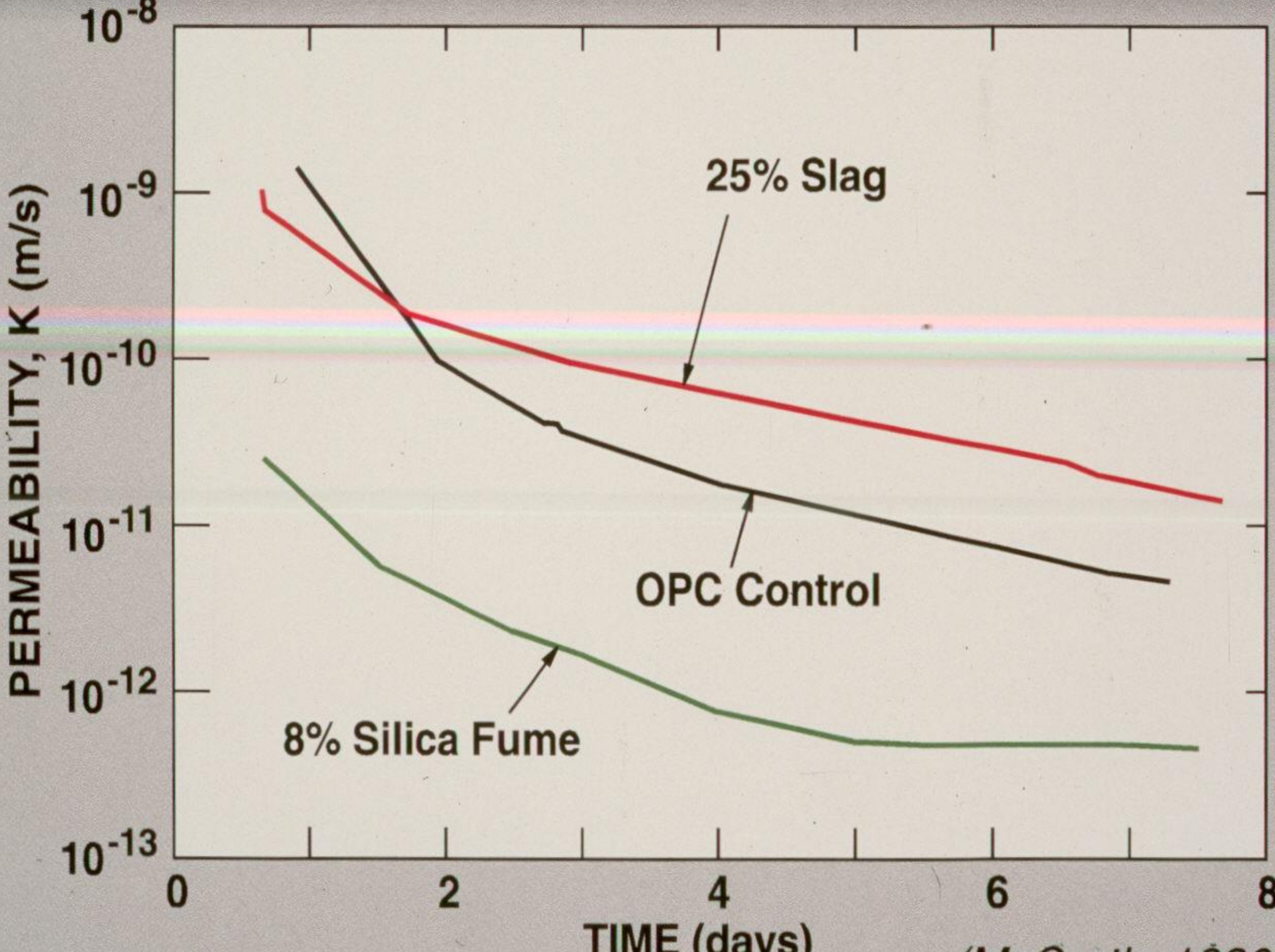
Admixtures add to cost of HPC

Improved Resistance to Fluid Ingress

- Silica Fume results in improved resistance to fluid penetration at early ages, but has less effect at later ages.
- Slag results in improved resistance to fluid penetration at ages beyond ~14 days that continues to further improve for along time.
- Using ternary mixtures gives the benefit of improved resistance at early ages combined with continued long-term improvements

REDUCTION IN EARLY AGE WATER PERMEABILITY

of w/cm=0.45 Mortars



(McGrath, 1996)

Effect of Slag on Concrete (= [W] and w/cm)

Slag %	Water	W/CM	91-day Strength (MPa)	RCPT (coulombs)	Permeability H_2O 10^{-13} m/s
0	200	0.45	35.8	5200	10.1
25	200	0.45	42.7	2450	5.4
50	200	0.45	42.8	1020	2.3

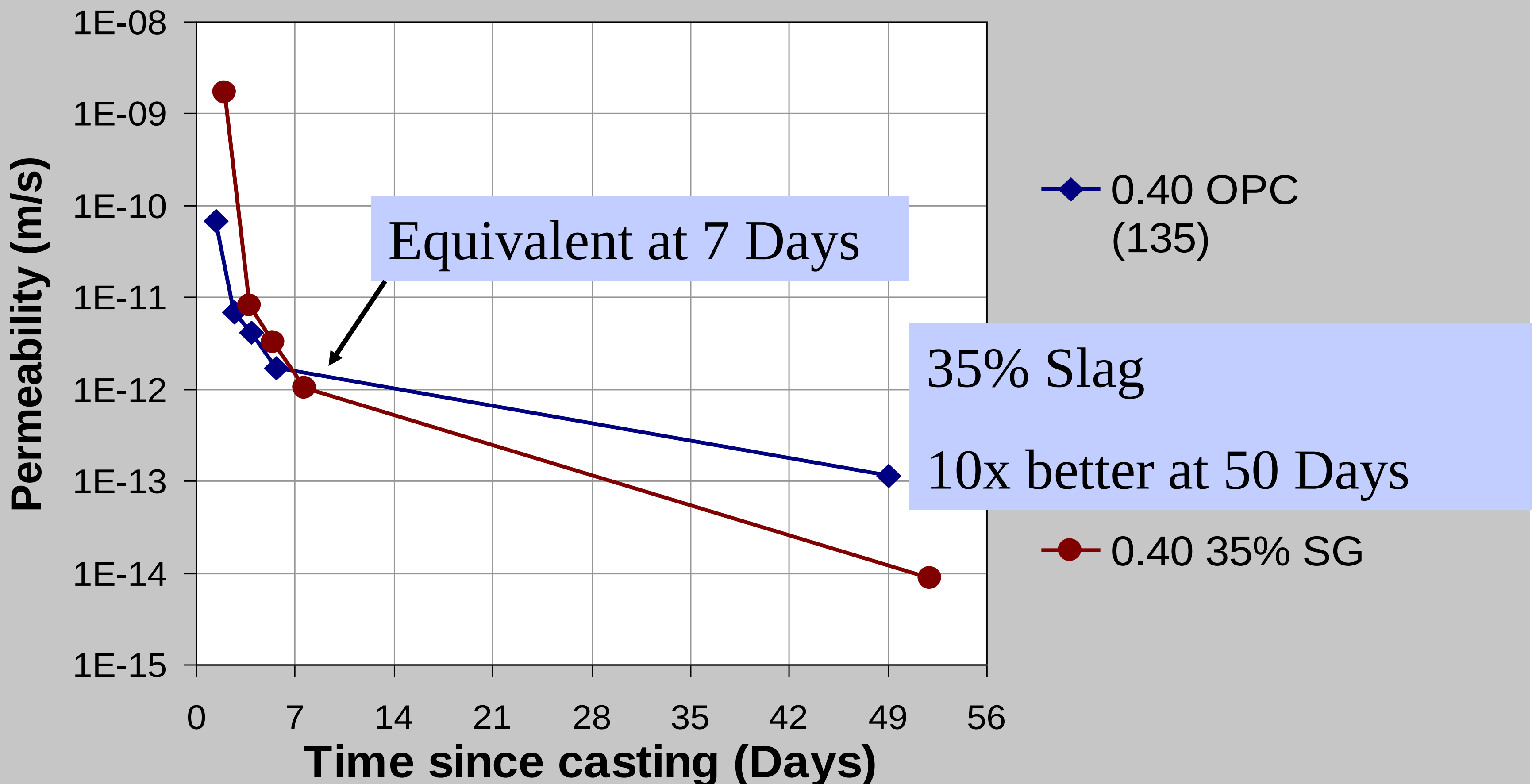
5.1x

4.4x

R. Bin Ahmad, 1991

Early-Age Concrete Permeability Results: Effect of Slag

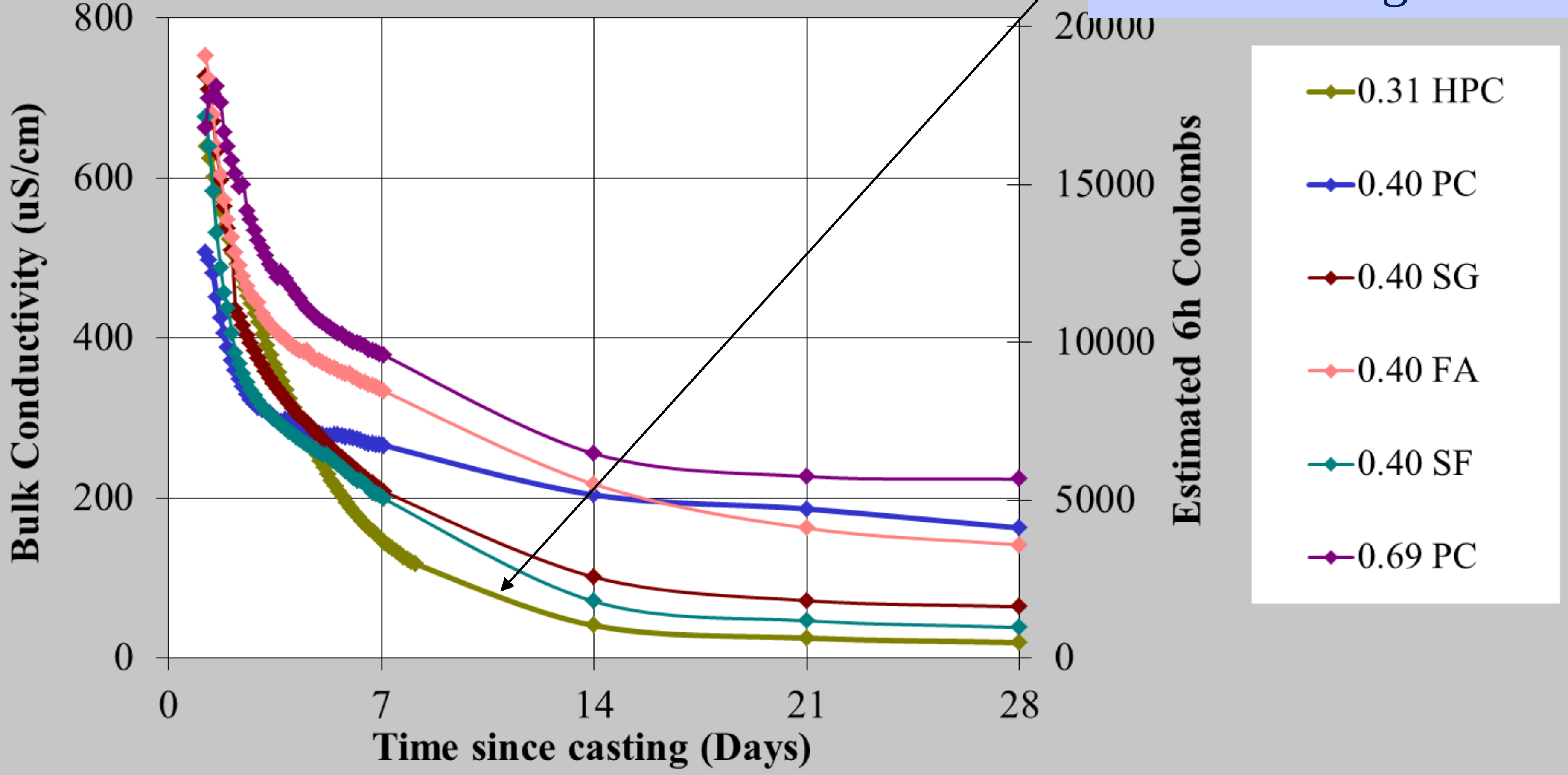
(calculated on inflow up to 7 days)



Nokken and Hooton, 2003

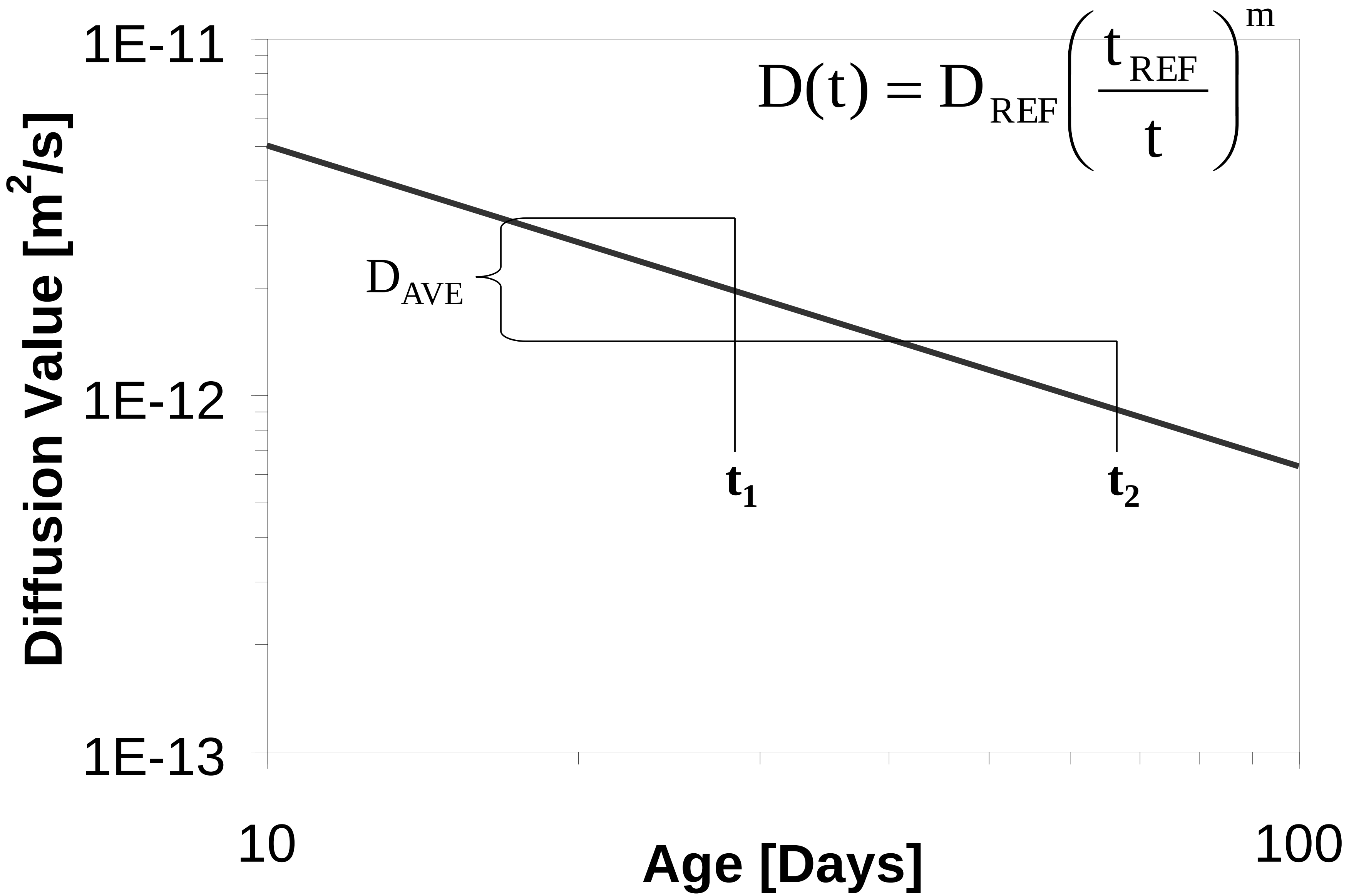
Bulk Conductivity to 28 days

HPC mix has 6% SF and 25% Slag

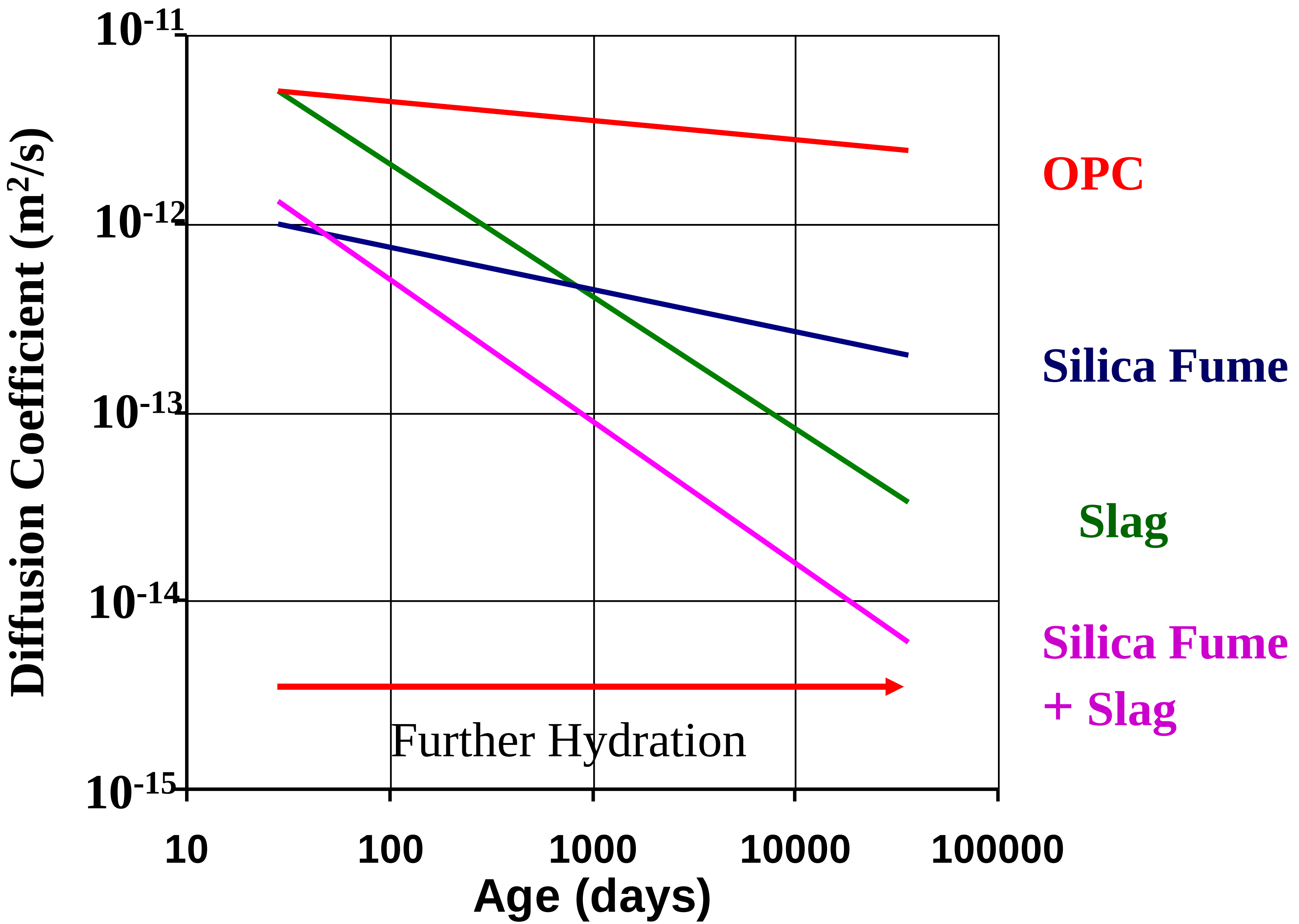


Nokken & Hooton 2004

Diffusion rates decrease with time

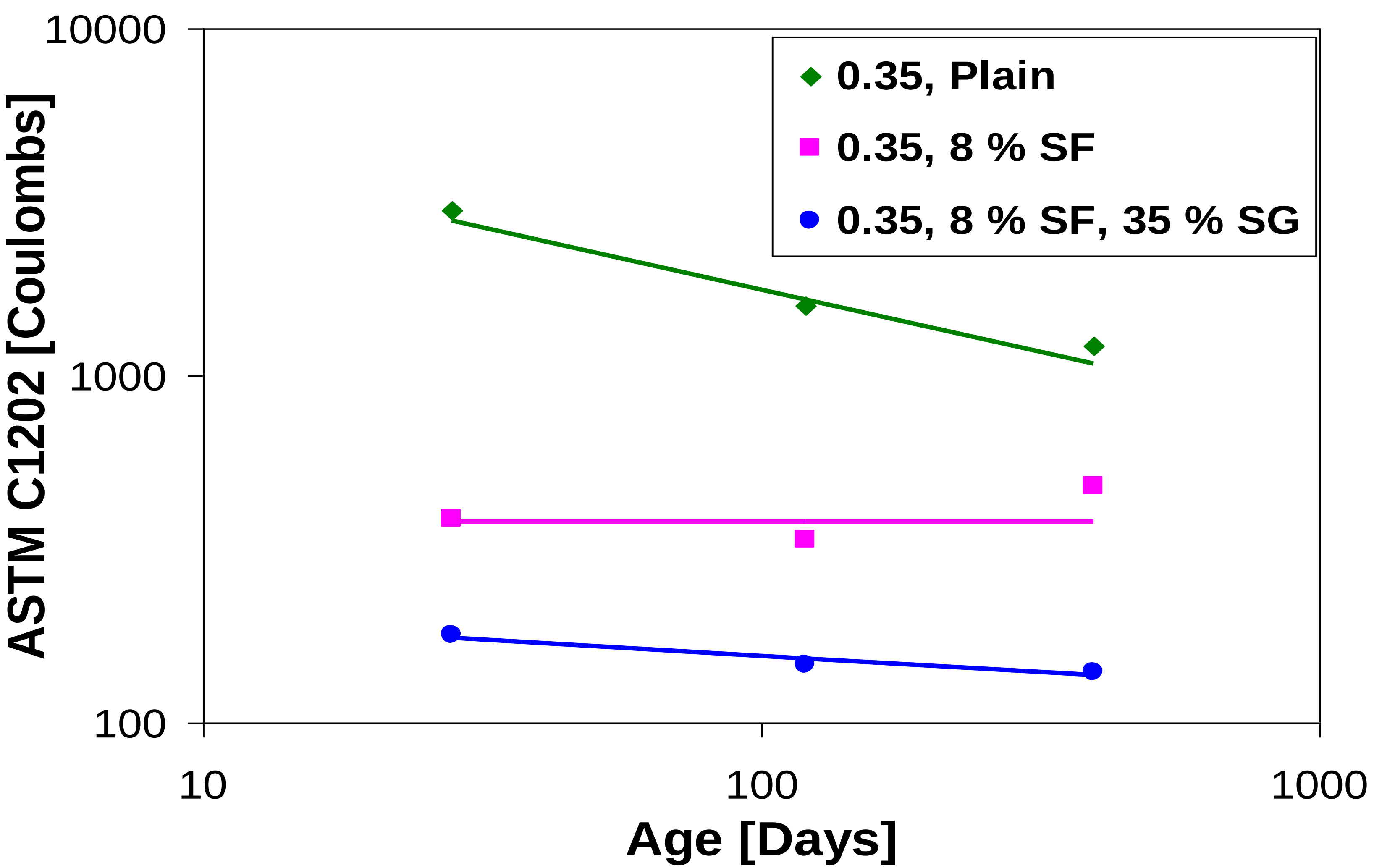


Ternary Blends –Time -Dependant Diffusion

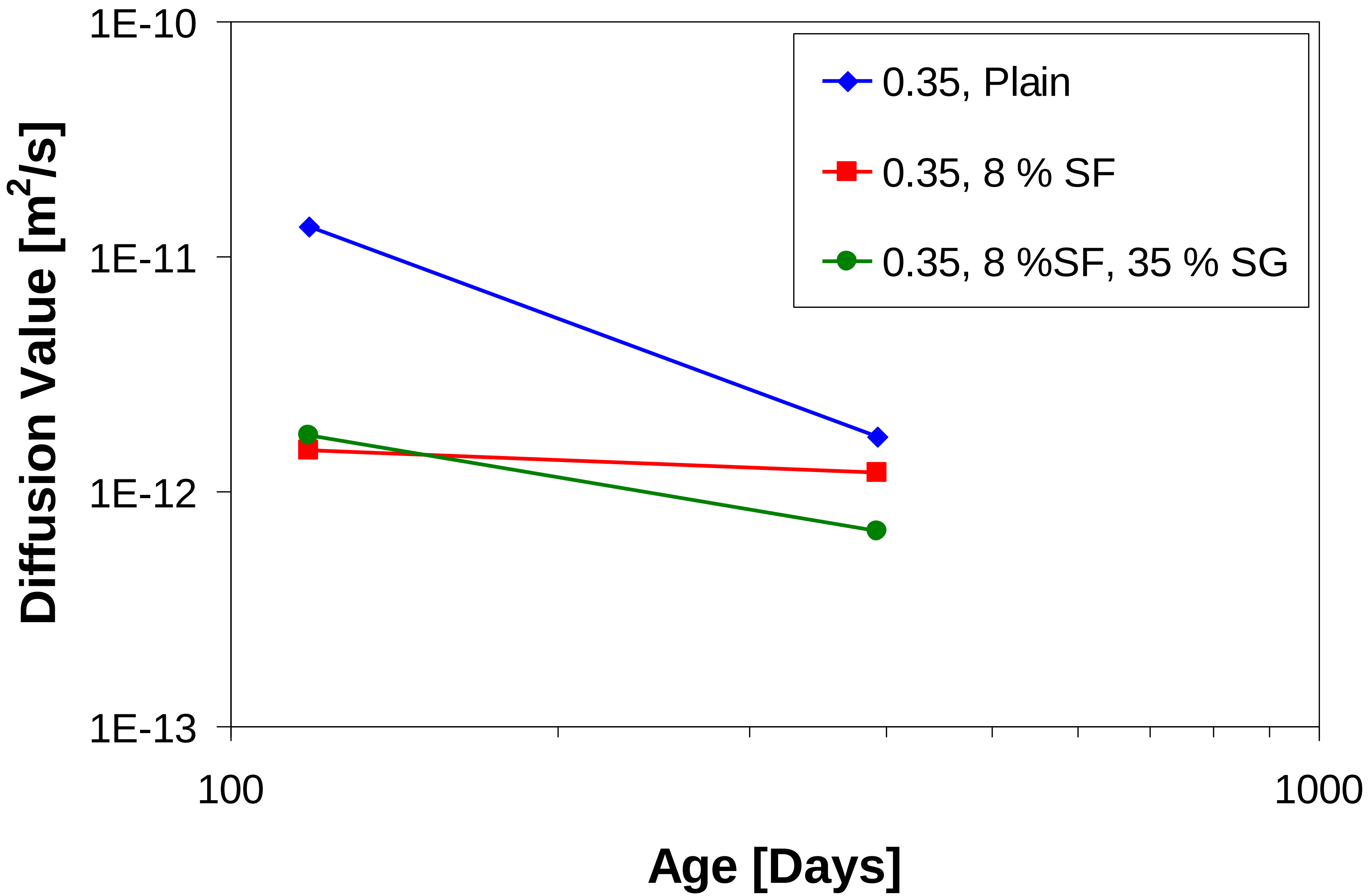


Thomas, 2000

ASTM C1202 Chloride Penetration Resistance -



Chloride Bulk Diffusion



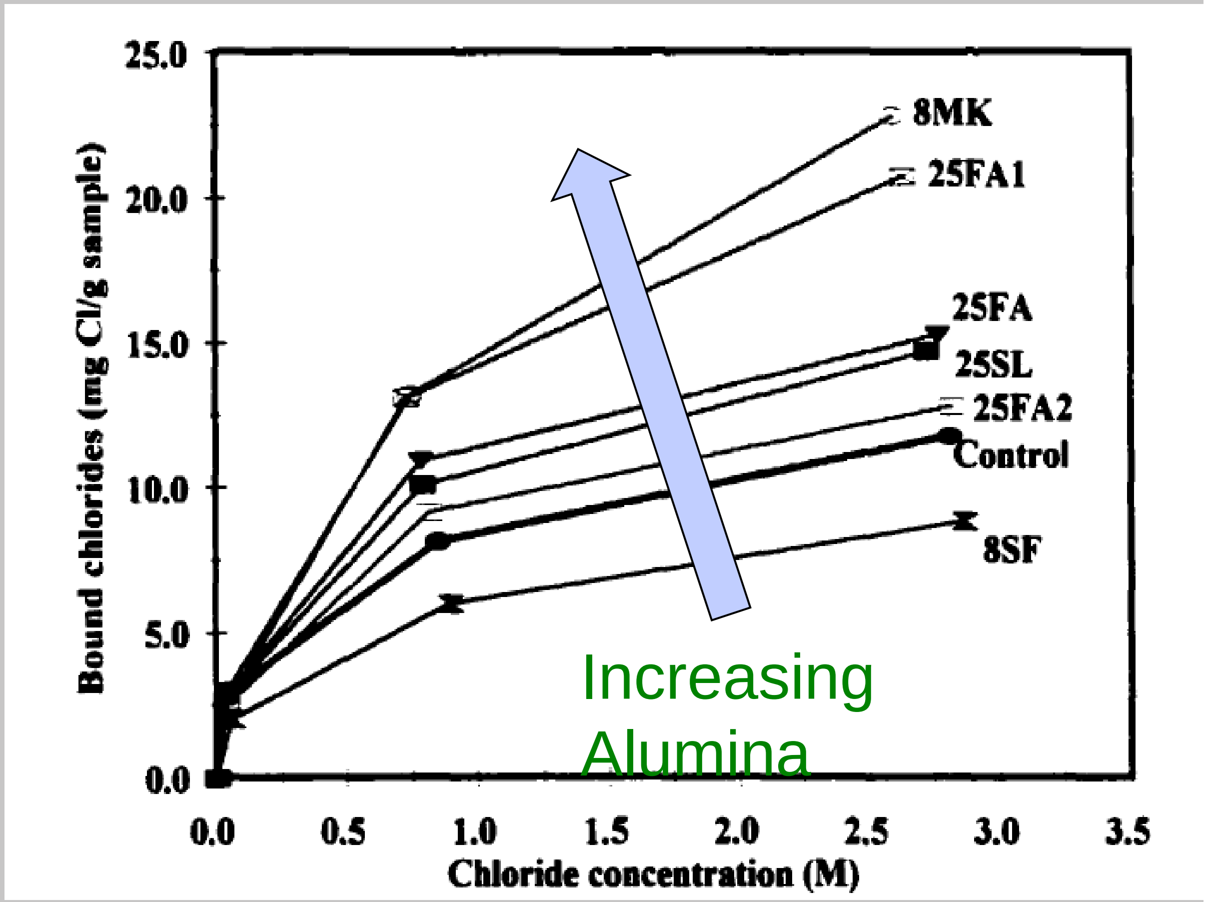
Water Permeability of Concretes
at 90 days (cured 4 days)

Cement	w/cm	K (m/s)
OPC	0.69	3.7×10^{-12}
OPC	0.49	2.8×10^{-13}
8% SF + 25% Slag	0.29	2.0×10^{-16}

El-Dieb & Hooton
1995, CCR

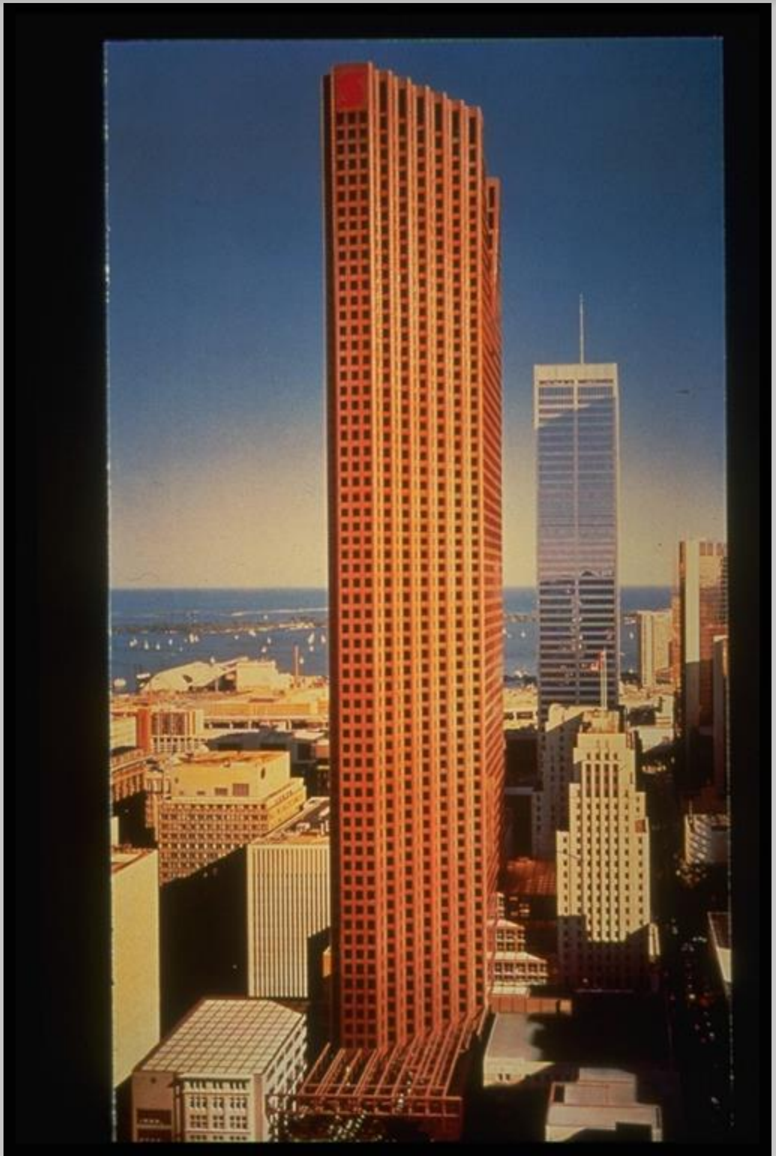
Effect of Alumina in SCMs on chloride binding

- w/cm = 0.5 @ 56d
- 25% Slag or Fly Ash increases binding
- 8% Silica Fume decreases chloride binding
- Ternary mixes result in increased levels of binding.



H. Zibara, PhD Thesis, U of T

Scotia Plaza Toronto



- Built in 1986-87.
- The first of >10 towers in Toronto to use silica fume plus slag (7.8%+25%).
- 70MPa specified strength (later ones were 85 Mpa)
- All concrete was truck mixed, cooled with liquid nitrogen, and pumped .
- Slumps were >200mm and 90d strengths >90MPa at w/cm=0.31.

High Strength Concrete in Toronto (70 MPa)

	Scotia Plaza	BCE Place Phase I	BCE Place Phase II	Bay Adelaide	Simcoe Place
No. Tests	143	287	294	93	139
91 day strength	93	87	94	95	93
Std. dev. (MPa)	6.8	8.1	6.0	5.8	5.1
C.V. (%)	7.3	9.3	6.4	6.1	5.5

Before SF-blended cements (Scotia Plaza, BCE Place Phase I)

Courtesy of J.Ryell

High Strength Concrete in Toronto (85 MPa)

	BCE Place Phase II	Bay Adelaide	Simcoe Place
No. Tests	281	137	97
91 day strength	99	97	105
Std. dev. (MPa)	5.6	5.3	5.2
C.V. (%)	5.7	5.4	5.0

Courtesy of J.Ryell

Ternary Cements for Pre-Cast Concrete

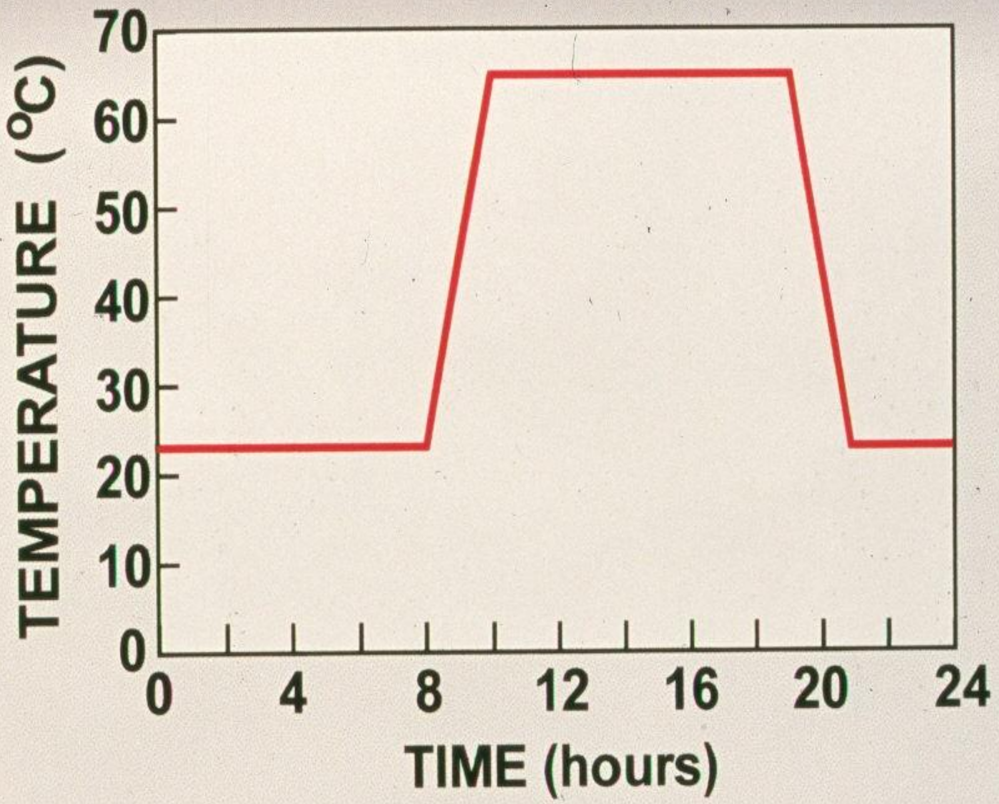
- Ternary systems can develop high-early strength in accelerated curing and help prevent ASR and chloride penetration.
- 18h strengths are similar to Type HE cements for release of PT wires.
- Chloride resistance of 65^{o}C-cured ternary concrete is not adversely affected, unlike Type HE portland cement.

Concretes

W/CM=0.3, CM=460kg/m^3, 5-8%Air, Slump=150-200mm

Accelerated Curing Program

- *23°C until initial set (6-8 h)*
- *20°C/h rise to 65°C*
- *Hold at 65°C for 9 h*
- *Cool at 20°C/h*



Results compared to moist curing at 23°C

Strength after 65^{o}C Cure(MPa)
(7.5% Air, 150-200mm Slump)

Concrete	18 Hour	28 Day
OPC	31.2	45.4
4% SF	40.9	55.8
8% SF	45.4	54.1
8% SF+ 25%Slag	40.5	58.1

RCPT (coulombs) at 28days

Cementing Materials	23C 6 days moist	65C heat + air cured	RCPT 65C/ RCPT 23C
OPC	2280	3120	1.4x
4% SF	520	1050	2.0x
8% SF	270	230	0.9x
4% SF + 25% slag	310	-	
8% SF + 25% slag	170	130	0.8x
T10 SF + 25% slag	260	-	

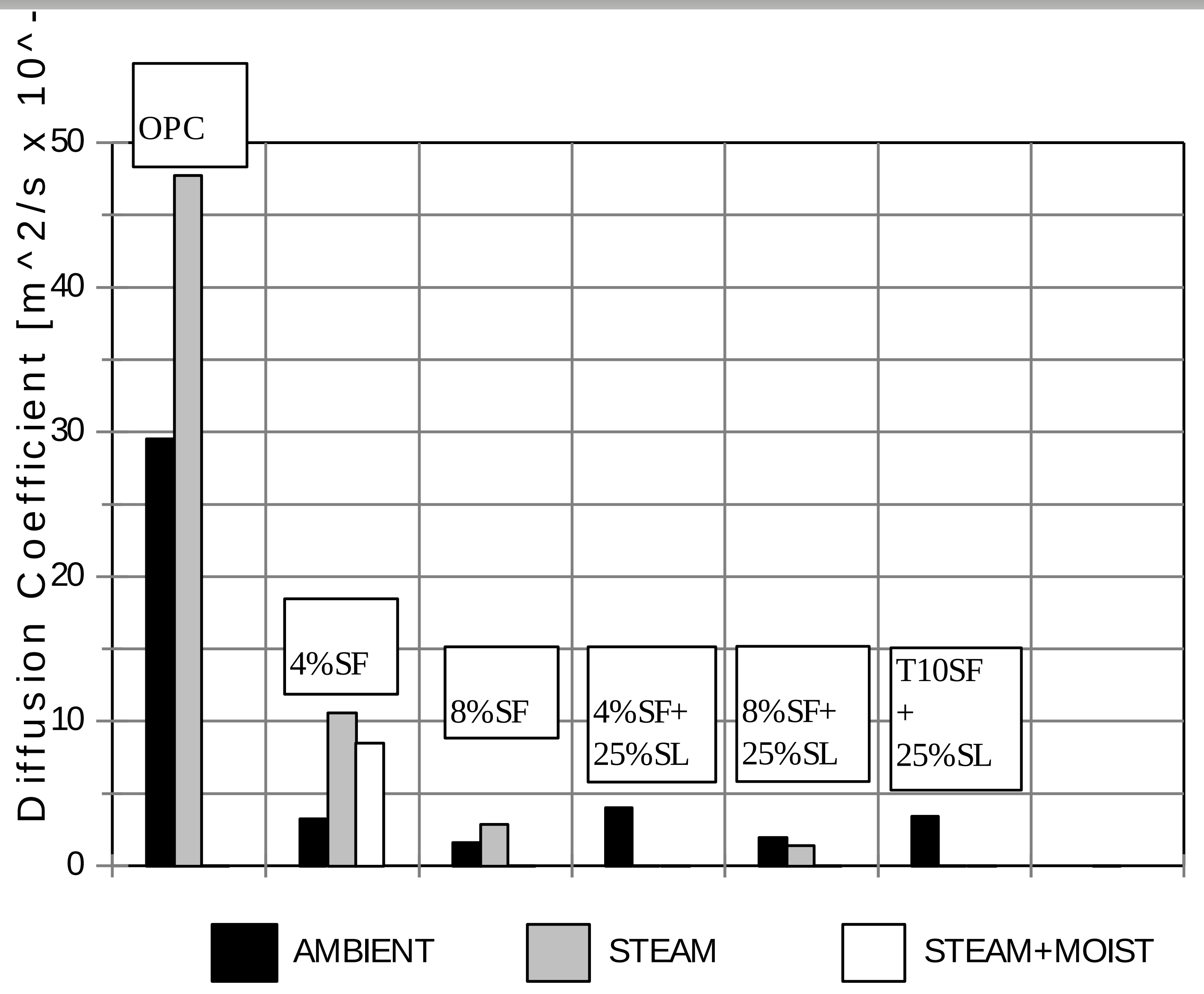
120 Day Chloride Bulk Diffusion

Concrete	D_a 10^{-12} m^2/s 23^oC Cure	D_a 10^{-12} m^2/s 65^oC Cure
GU Cement	32.7	61.4
4% SF	4.3	13.4
8% SF	2.4	3.8
4% SF+25% S	4.4	-
8% SF+25% S	2.7	3.3
GUbSF+25%S	4.5	-

Titherington & Hooton 2004

w/cm = 0.30 air-entrained mixes

120 Day, 5M, 40^{o}C Chloride Diffusion



TTC - Subway Toronto

	Actual	Specified
Type 10SF (kg/m^3)	305	} 400 min
Slag (kg/m^3)	145	
W/CM	0.31	0.35 max
28-day Strength (MPa)	74.9	60 min
D_a (x 10^{-15} m^2/s)	621	1500 max
k (x 10^{-15} m/s)	1.34	100 max

Summary of Diffusion Coefficients and ASTM C1202 Rapid Chloride Permeability Values for TTC Subway Project

Die Cast	Chloride Diffusion $\times 10^{15}$ m^2/s			Rapid Chloride Permeability	
	40D	80D	120D	Charge Passed after 6 hours (Coulombs)*	Age at Test (months)
April 30/96	1,087	480	783	434	11
June 11/96	583	574	784	484	10
July 23/96	604	1,030	590	443	9
Sept. 12/96	1,320	1,112	517	515	7
Oct. 24/96	510	464	325	394	5
Dec. 5/96	499	429	972	91	4

*Cores stored moist for initial 28 days, then in air until tested.

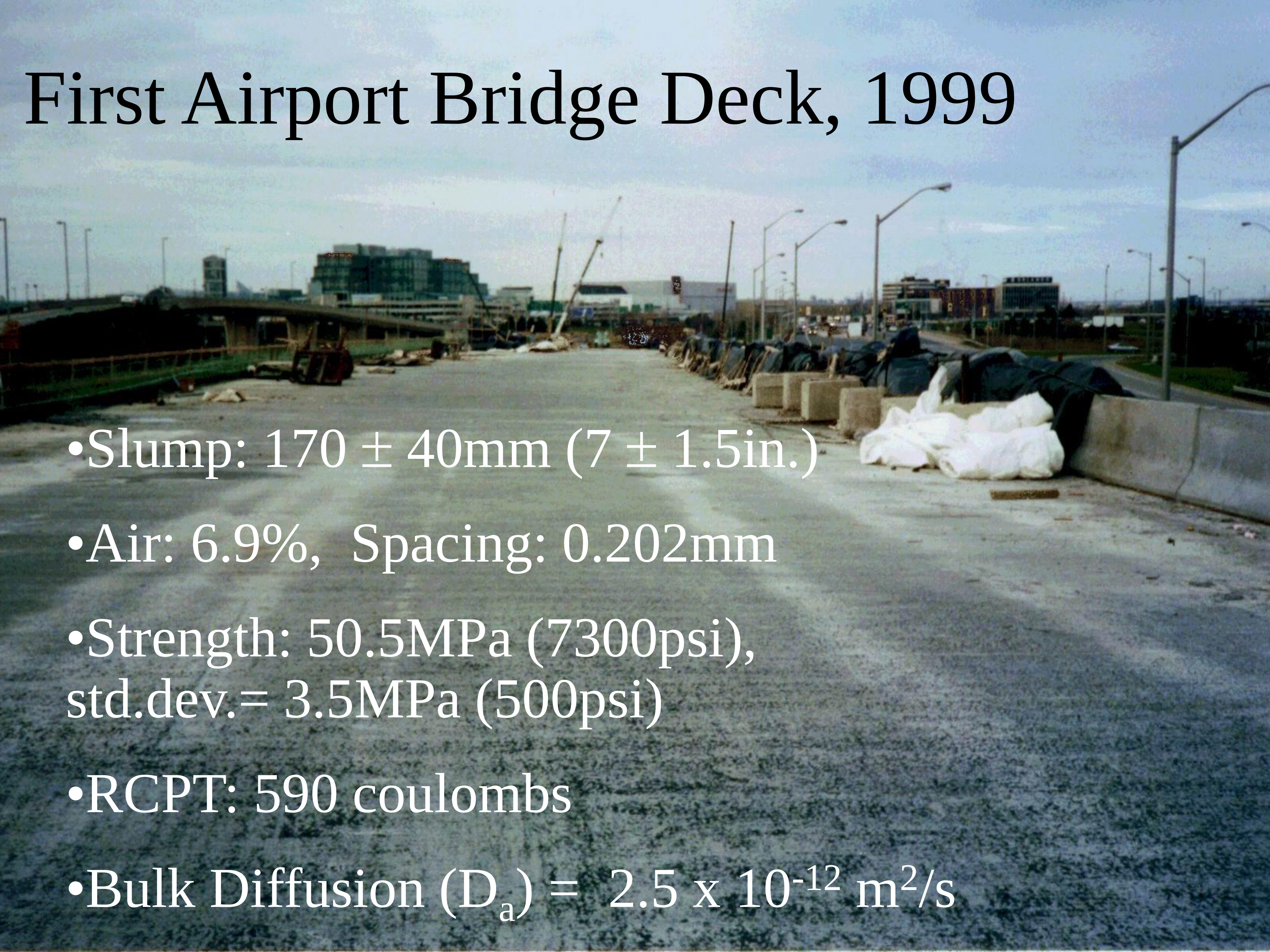
ref. Hart, Ryell, and Thomas, 1997

Bridge Decks at Toronto Airport

- In 1999, 4 bridge decks were placed using Type GUbSF cement + 25% Slag at 0.40 w/cm using the MTO High Performance Concrete Spec. but spec'd at 35MPa (but >50MPA achieved)
- High corrosion resistance was required.
- The concretes were placed in cold weather in 16h continuous placements of 1200m^3.
- After that, 40 bridge structures and terminal decks at the airport used similar concrete mixtures.

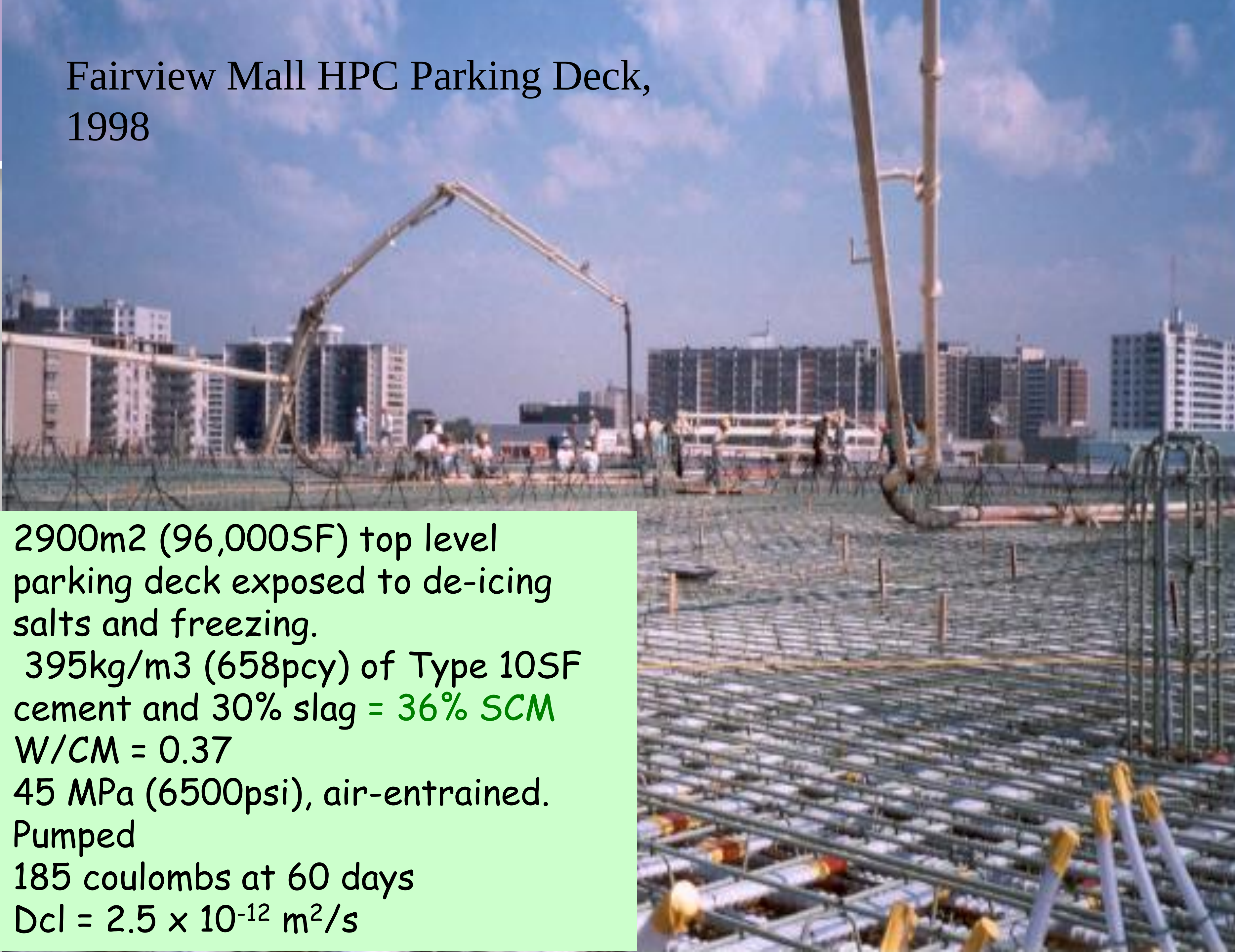
The bridges have been recently inspected and all are performing well.

First Airport Bridge Deck, 1999



- Slump: 170 ± 40mm (7 ± 1.5in.)
- Air: 6.9%, Spacing: 0.202mm
- Strength: 50.5MPa (7300psi), std.dev.= 3.5MPa (500psi)
- RCPT: 590 coulombs
- Bulk Diffusion (D_a) = 2.5×10^{-12} m^2/s

Fairview Mall HPC Parking Deck, 1998



2900m2 (96,000SF) top level parking deck exposed to de-icing salts and freezing.

395kg/m3 (658pcy) of Type 10SF cement and 30% slag = 36% SCM

W/CM = 0.37

45 MPa (6500psi), air-entrained.

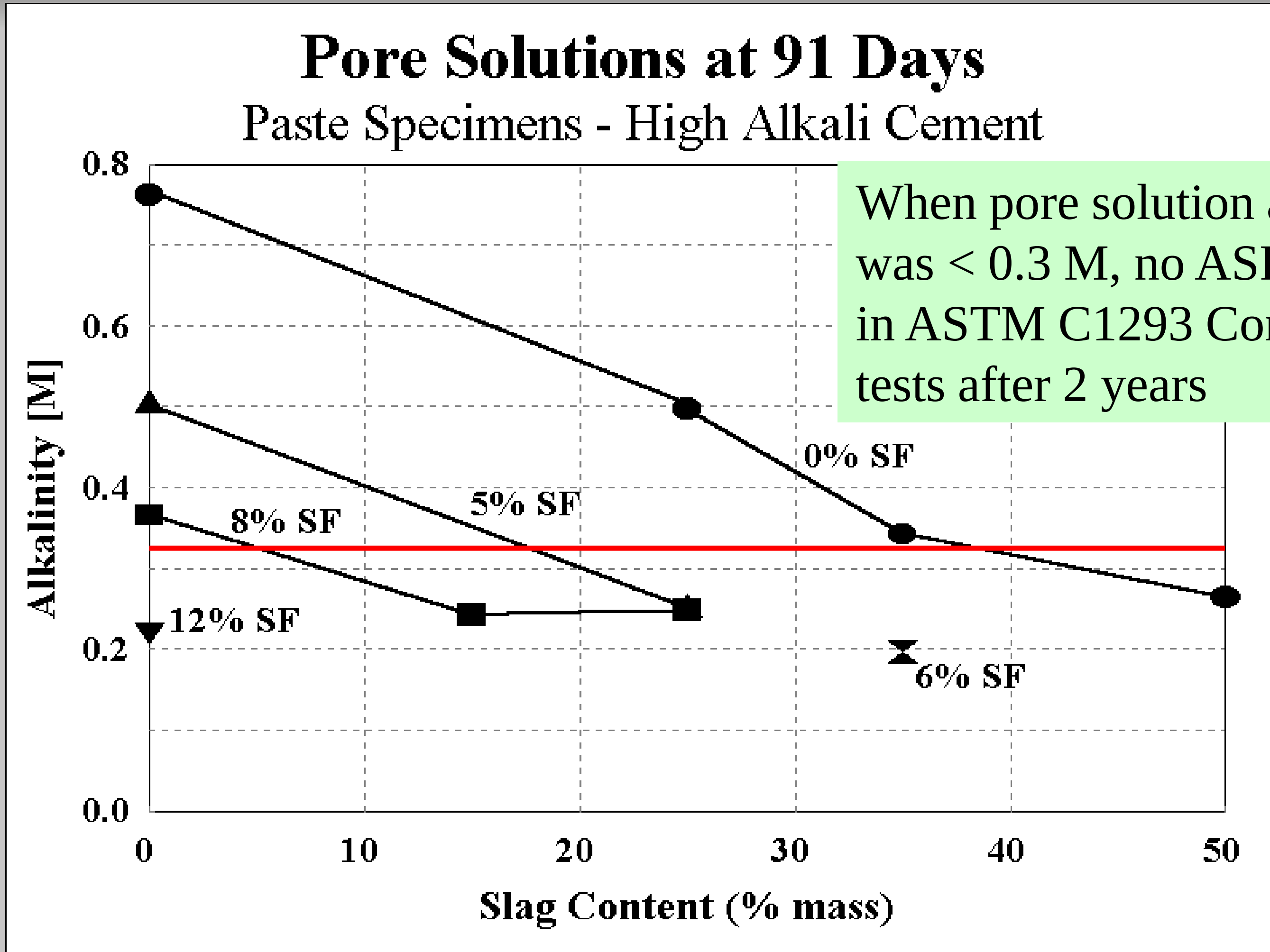
Pumped

185 coulombs at 60 days

Dcl = 2.5×10^{-12} m^2/s

ASR

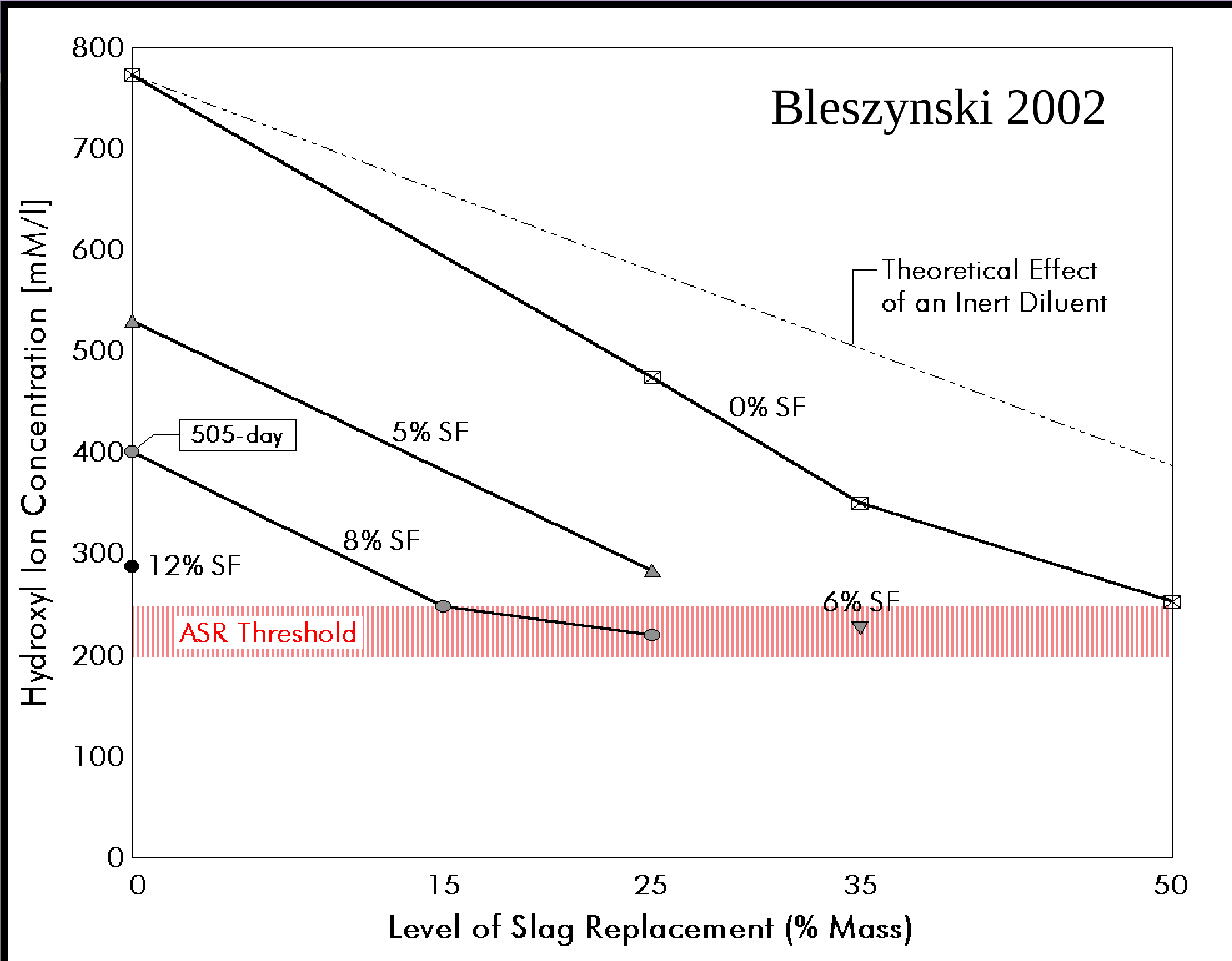
Reduction in Pore Solution Alkalinity with SCMs (Slag + SF)



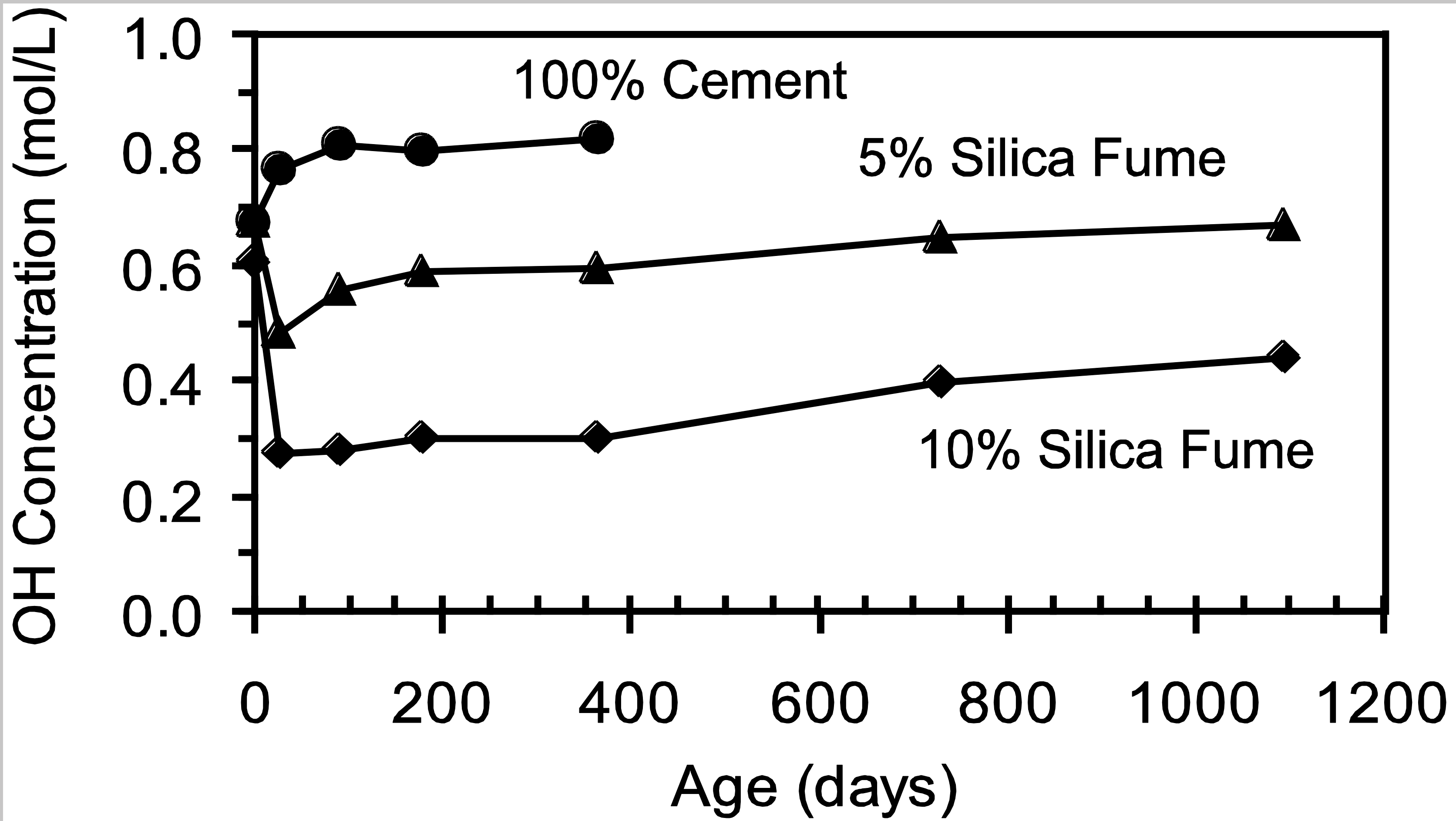
When pore solution alkalinity was < 0.3 M, no ASR expansion in ASTM C1293 Concrete prism tests after 2 years

(Bleszynski, Hooton & Thomas)

2-Year Paste Specimen Pore Solution Alkalinity



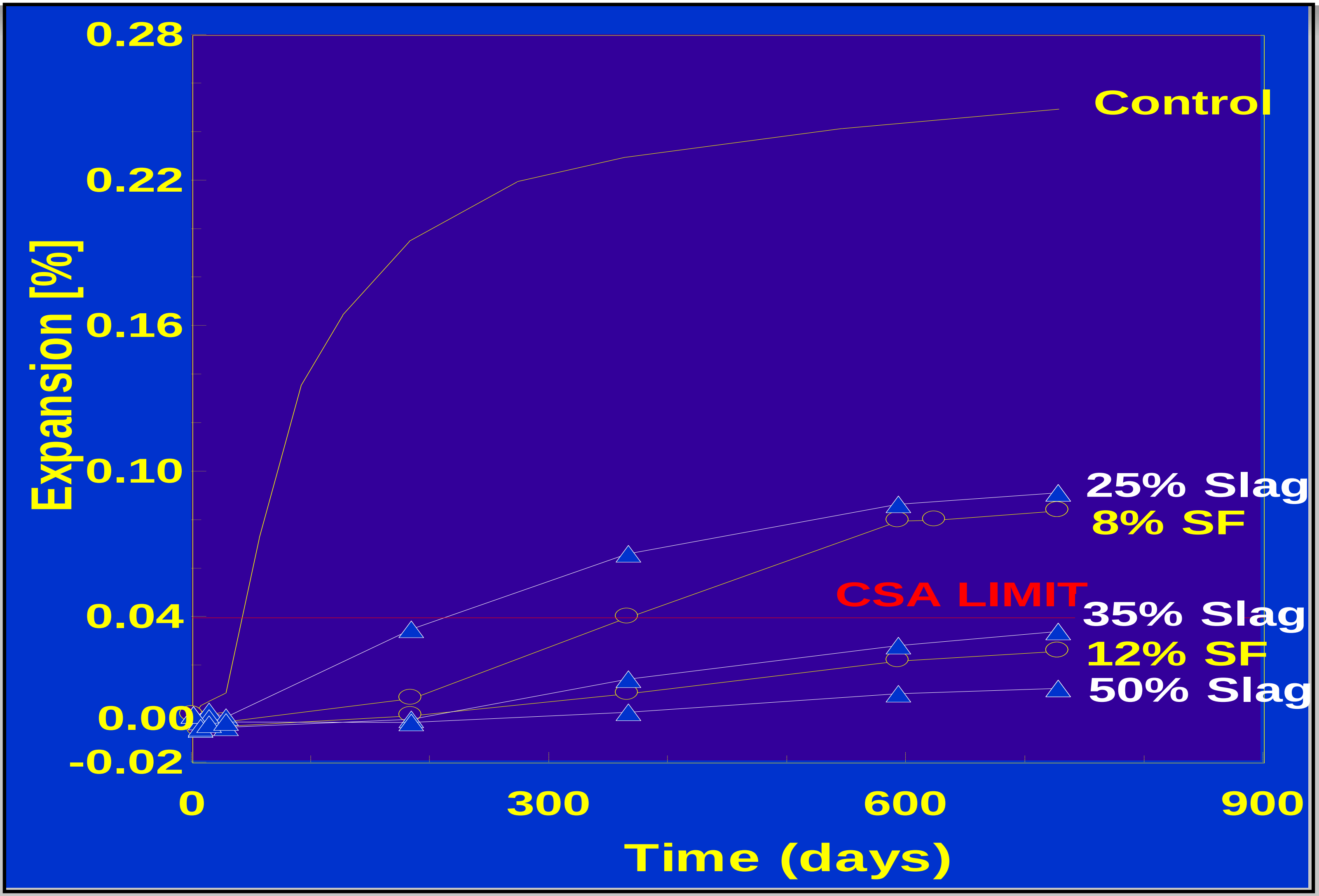
But without Alumina to stabilize the alkali in the C-S-H, alkali is slowly released to the pore solution



Shehata and Thomas 2002

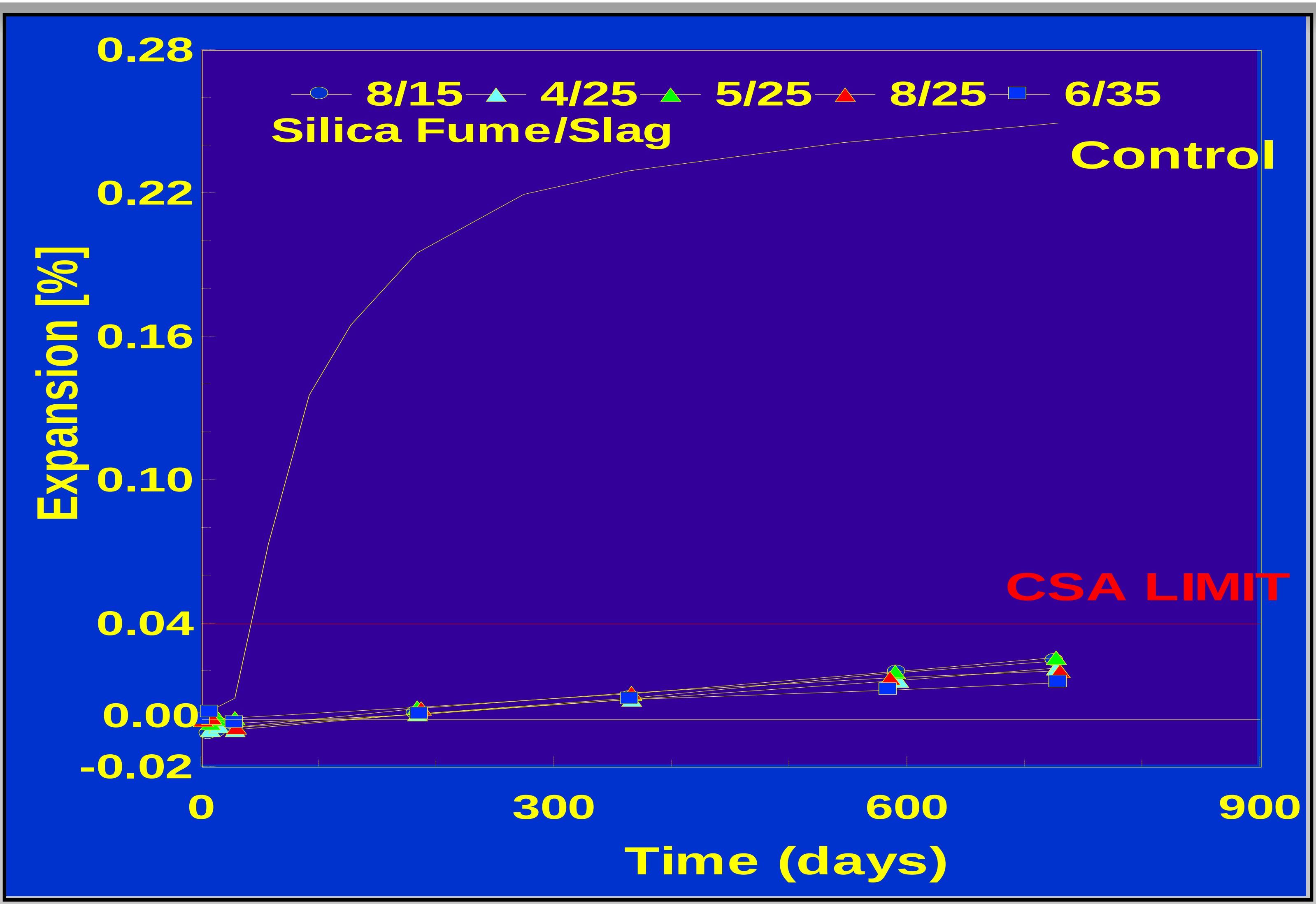
Thomas 1998

Concrete Prism Expansion
Spratt Aggregate - Silica Fume or Slag

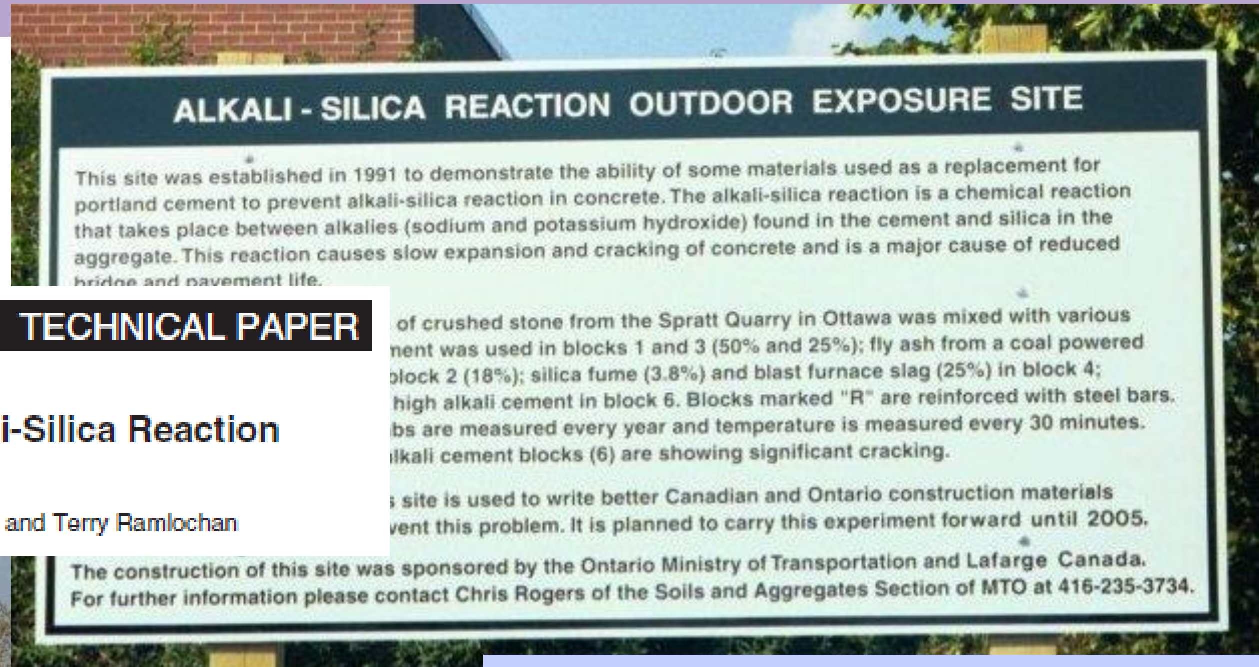


Bleszynski et al

Concrete Prism Expansion
Spratt Aggregate - Ternary Blends



1991 MTO Site Kingston, Ont.



ACI MATERIALS JOURNAL — TECHNICAL PAPER

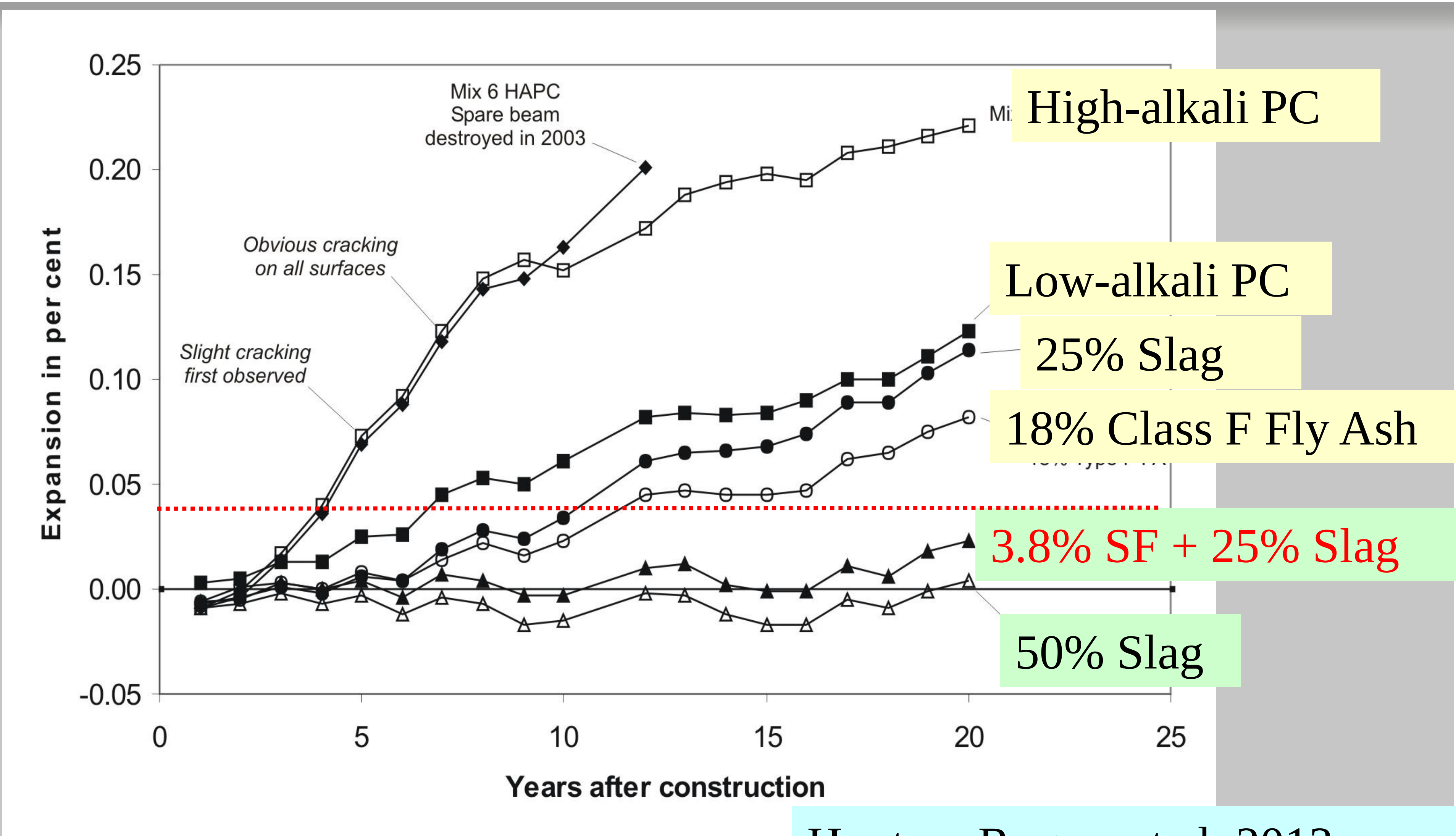
Title no. 110-M49

Twenty-Year Field Evaluation of Alkali-Silica Reaction Mitigation

by R. Doug Hooton, Chris Rogers, Carole Anne MacDonald, and Terry Ramlochan

6 Concretes: 420kg/m^3,
Spratt Agg.
HAPC
LAPC
25% slag
50% slag
18% fly ash
25% slag + 3.8% silica fume

20-year old 0.6x0.6x2.0 m concrete beams exposed outdoors in Kingston (mixes: 420kg/m^3)



Hooton, Rogers et al, 2013

Strengths of Air-entrained Concretes cured at 23 ^oC with limestone and SCMs

Mix Identification (all 400 kg/m3 (666 pcy mixes)	% clinker in binder	w/cm	Compressive Strength (MPa)			
			7 day	28 day	56 day	182 day
GU Cement Control	89*	0.40	39.3	45.5	50.7	52.6
GU + 40% Slag	53	0.40	32.8	46.2	49.2	51.2
GUL9 + 40% Slag	50	0.40	36.1	50.9	53.6	50.7
GUL9 + 50% Slag	41	0.40	34.6	49.0	53.0	51.0
GUL15 + 40% Slag	46	0.40	37.1	52.3	57.5	59.2
GUL15 + 50% Slag	38	0.40	36.3	55.3	60.1	65.6
GUL15+ 6% Silica Fume + 25% Slag	53	0.40	46.0	65.0	70.1	76.0

* 3.5% limestone and 8% gypsum

U. of Toronto Field site data

Permeability Index of Air-entrained Concretes cured at 23 ^{o}C with limestone and SCMs

Mix Identification (all 400 kg/m^3 (666 pcy mixes)	% clinker in binder	w/cm	Rapid Chloride Permeability ASTM C1202 (Coulombs)		
			28 day	56 day	182 day
GU Cement Control	89	0.40	2384	2042	1192
GU + 40% Slag	53	0.40	800	766	510
PLC 9% + 40% Slag	50	0.40	867	693	499
PLC 9% + 50% Slag	41	0.40	625	553	419
PLC 15% + 40% Slag	46	0.40	749	581	441
PLC 15% + 50% Slag	38	0.40	525	438	347
PLC 15% + 6% Silica Fume + 25% Slag	53	0.40	357	296	300

CSA A23.1 limit is 1500 coulombs @ 56d for C-1 Exposure

Summary

- Ternary cementitious systems work synergistically to combine the best properties of both Slag and Silica Fume.
- High-Performance Concretes are easier to produce, place, and finish with ternary systems.
- Physical properties and durability are also enhanced at both early and later ages.

Conclusions

Appropriate ternary blend combinations exhibit greater performance than the control mix or mixes with a single SCM in terms of:

- Compressive strength (early and late age)
- Controlling damaging expansion due to ASR
- Resistance to the ingress of chlorides
- Resistance to sulfate attack

The de-icer salt scaling field performance of ternary mixes is also good.