International Trends in Beneficial Use of Fly Ash

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Honor of Dick Stehly

ACI Minneapolis April 14, 2013


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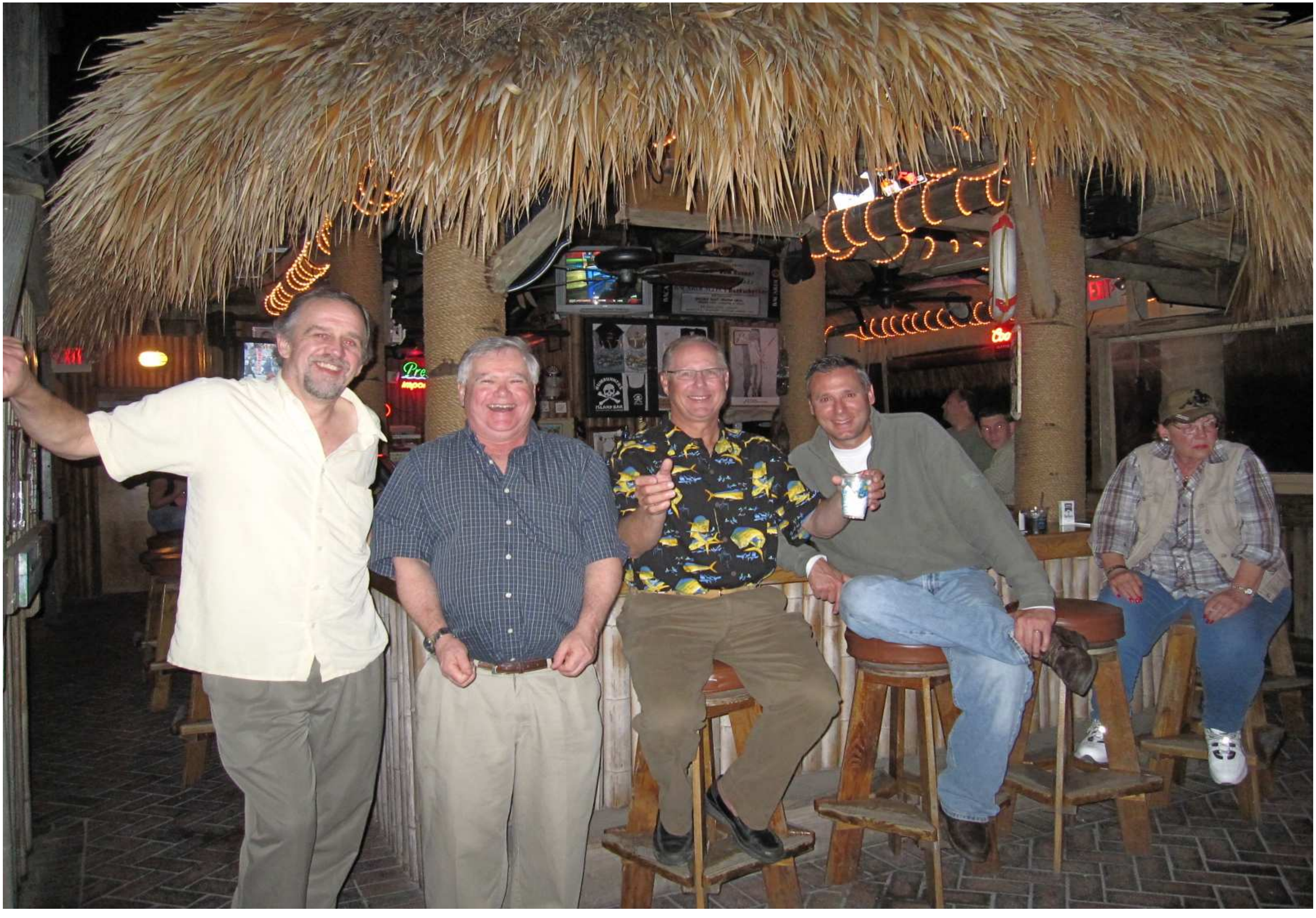


Canada

- The proportion of ash and all coal combustion products that is beneficially used in Canada has continued to increase and is now over 28%
- CIRCA, the Canadian equivalent of ACAA, continues to promote beneficial use.

CIRCA
ASSOCIATION OF
CANADIAN INDUSTRIES
RECYCLING COAL ASH

CANADA, PRODUCTION AND USE OF COAL COMBUSTION PRODUCTS (CCPs), 2009-2011 AVERAGE

	Fly Ash	Bottom Ash	Flue Gas Desulphurization Gypsum	Other (1)	Total CCPs
			(000 tonnes)		
PRODUCTION					
Produced	4,368	2,190	276	207	7,042
Disposed / Stored	3,010	1,777	1	205	4,993
Removed from Disposal	3	--	--	--	3
USE (DOMESTIC)					
Cement	399	147	2	34	581
Concrete / Grout	683	--	--	--	683
Mining Applications	97	--	--	--	97
Roadbase / Subbase	13	40	--	--	53
Wallboard	--	--	274	--	274
Other (2)	33	1	--	2	36
TOTAL USE	1,225	188	276	36	1,724
Individual Use Percentage	28	9	100	17	25

Source: Natural Resources Canada
March 15, 2013

(1) Circulating fluidized bed fly ash and bottom ash

(2) Includes waste stabilization and specialty uses such as mineral filler and flowable fill

2009-11: 28% of fly ash is being used, and 100% of FGD gypsum is used

Environment Canada

- The Canadian equivalent of EPA continues to maintain Coal Combustion Products as non-hazardous.

Canada

- In Canada, challenges to beneficial use of fly ash have resulted from changing power plant operations.
- Since 2012, powder-activated carbon has been used to scrub mercury from stack gasses in Alberta and Saskatchewan. This has impacted the ability to air-entrain concrete.
- New Hg-scrubbing additives are being tried that reduce the impact on AEA.

CSA Specifications

- In terms of specifications, CSA fly ash specifications are different from ASTM/AASHTO in that ashes are classified based on calcium content rather than the sum-of-oxides approach.
- Fly ash is also considered part of the cementitious system and the specifications are included with the cement standards.

CSA A3001

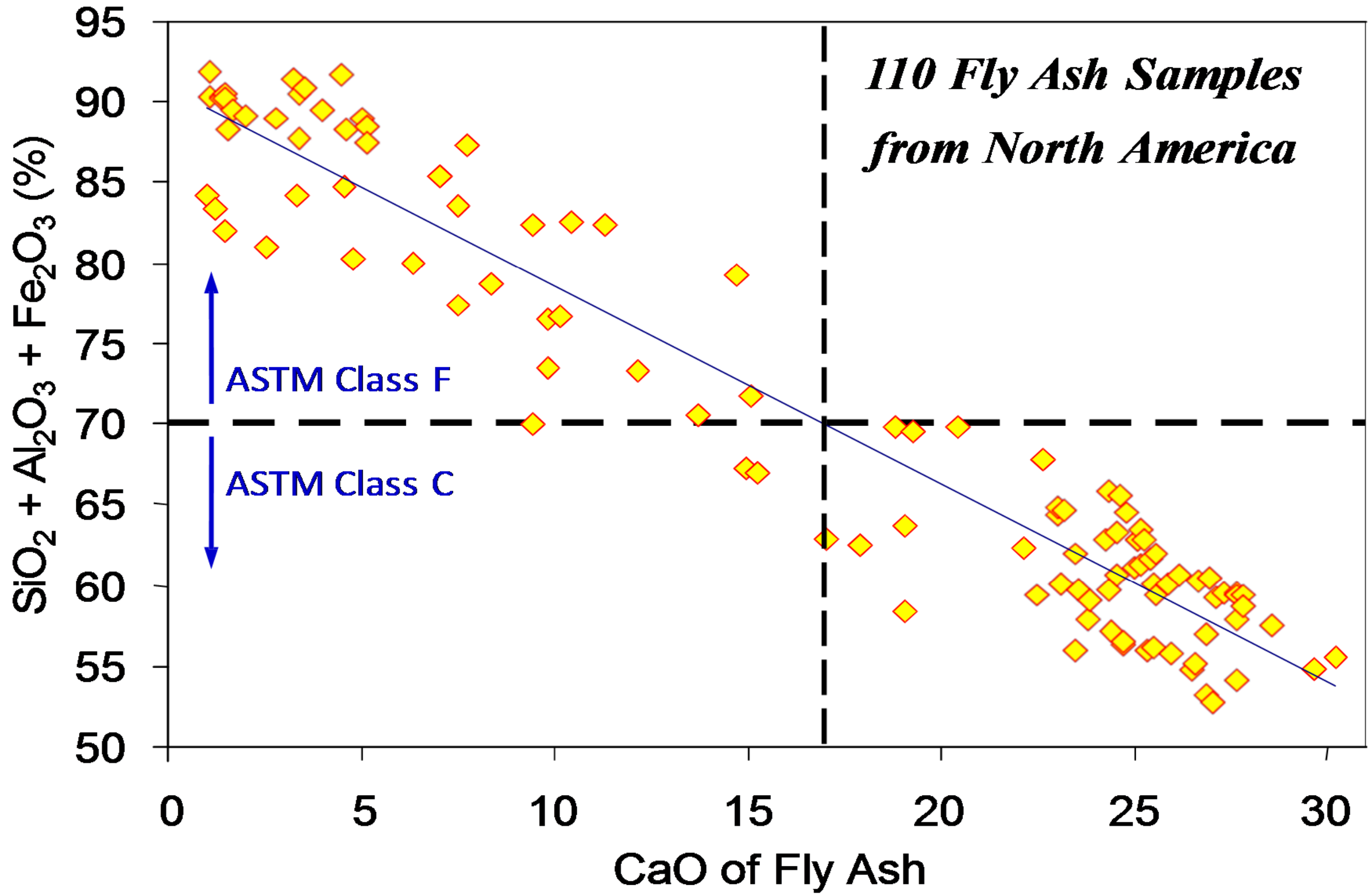
- Fly ashes are characterized by CaO content rather than the ASTM sum of the oxides.
- Class F ash has up to 15% CaO
- Class CI ash has 15-20% CaO
- Class CH ash has >20% CaO

- In addition for ASR mitigation, ashes are sorted by Na_2O_{eq}. as 0-3.0%, 3.1-4.5% and >4.5% (the req'd level of mitigation goes up as alkalis go up.

CSA A3001-2010 Revision

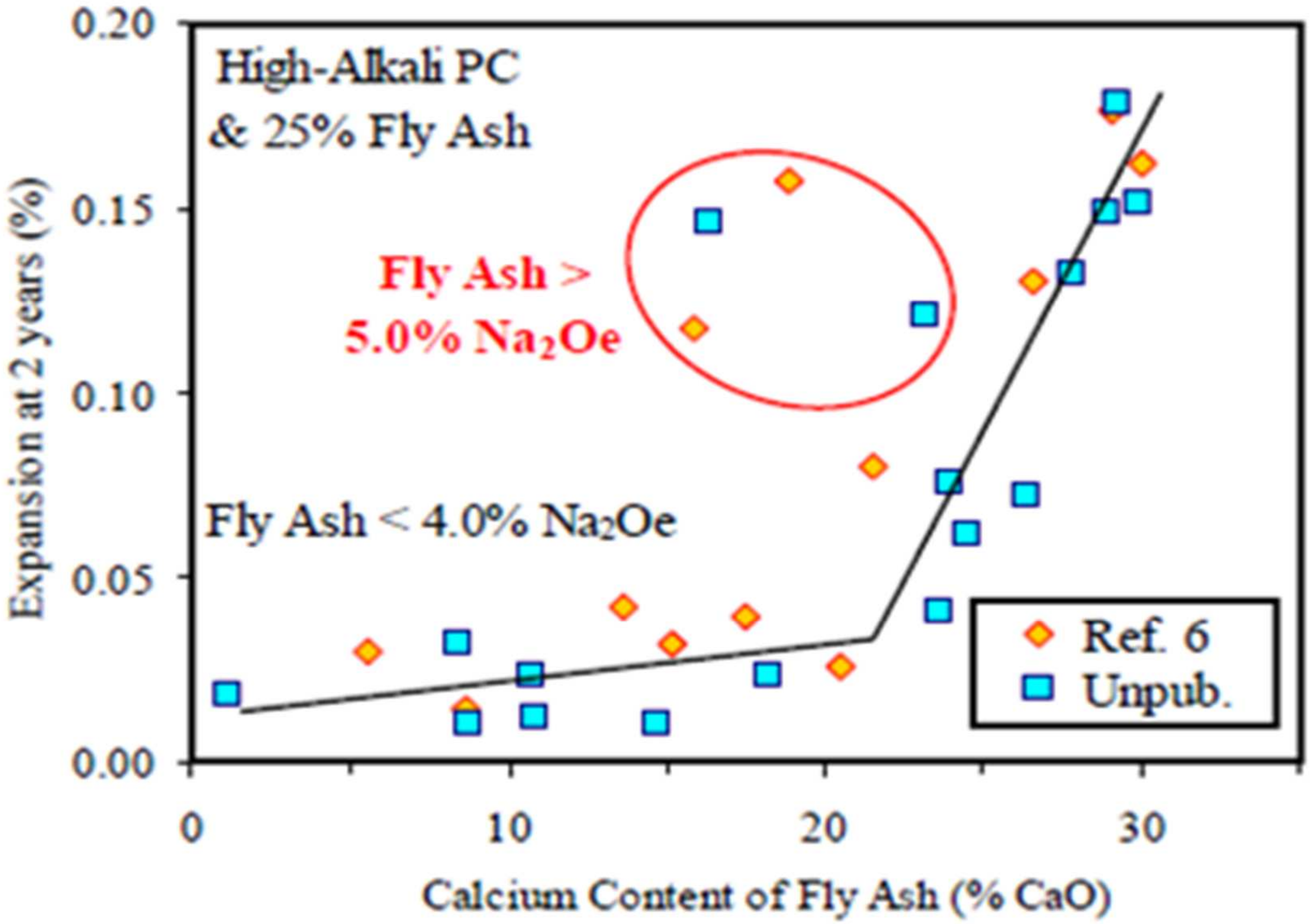
Table 7
Supplementary cementing materials and blended supplementary cementing materials — Chemical requirements
(See Clauses 3, 5.3, 5.4.1, and 5.4.2, Table 2, and CSA A3004-E1.)

	Type							
Property*	N	F	CI	CH	S	SF	SFI	Reference
Calcium oxide (CaO), %†	—	≤15	>15–≤20	> 20	—	—	—	CSA A3003
Sulphur trioxide (SO_3), maximum %‡	3.0	5.0	5.0	5.0	4.0**	1.0	1.0	CSA A3003
Sulphide sulphur (S)§, maximum %	—	—	—	—	2.5	—	—	CSA A3003
Loss on ignition, maximum %	10.0	8.0	6.0	6.0	—	10.0	10.0	CSA A3003
Silicon dioxide (SiO_2), minimum %	—	—	—	—	—	85	75	CSA A3003

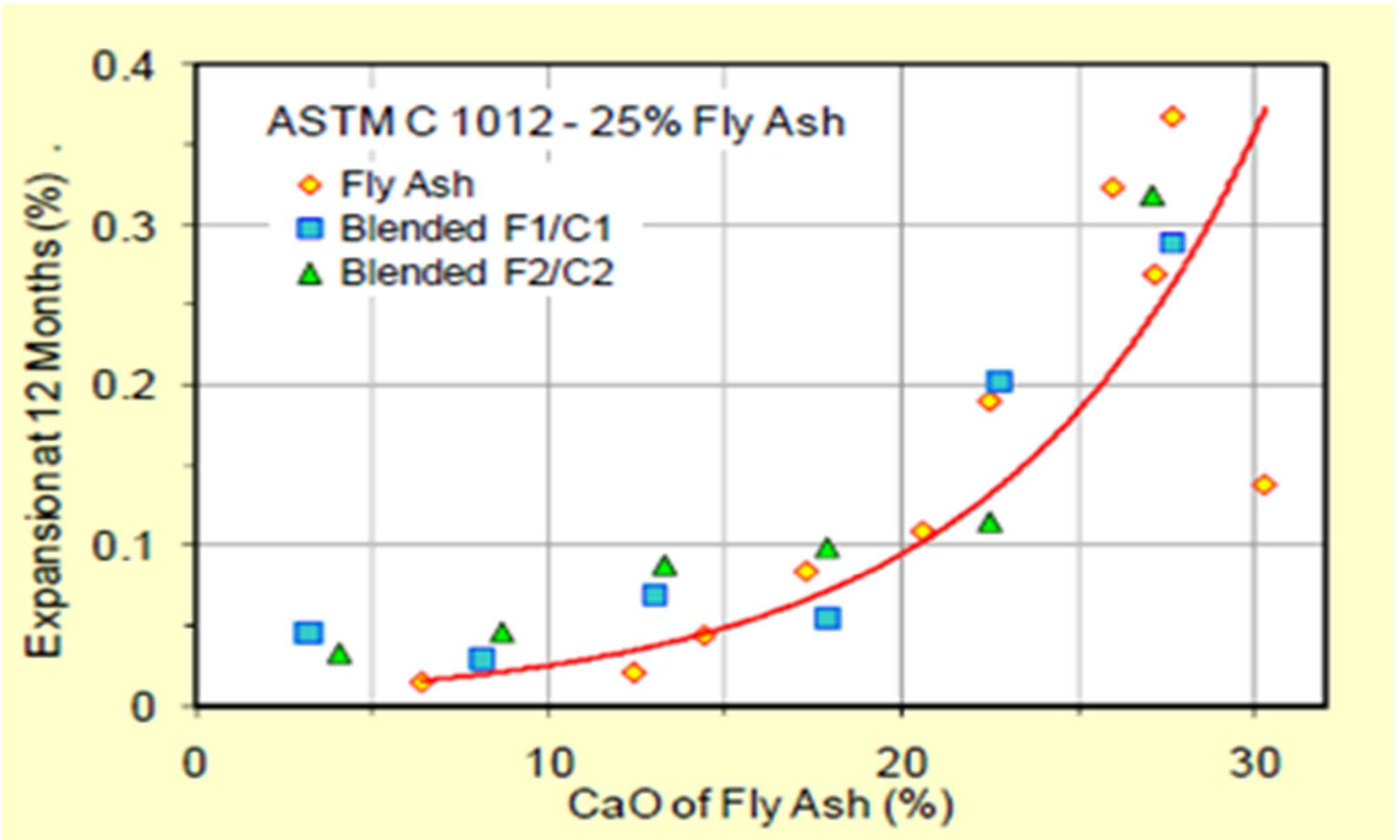


110 Fly Ash Samples
from North America
ASTM Class F
ASTM Class C
$SiO_2 + Al_2O_3 + Fe_2O_3$ (%)
CaO of Fly Ash
95
90
85
80
75
70
65
60
55
50
0
5
10
15
20
25
30

Effect of CaO and alkali on ASR Concrete Expansions



Effect of Fly ash CaO on Sulfate Resistance



CSA A3001

- In CSA, the strength activity test is optional.
- This is because the current test in ASTM C311, with the limits in C618 can not distinguish fly ash from inert fillers.
- Until a better test is developed, no test is specified.

CSA A3001 no Strength Activity test

Table 8
Supplementary cementing materials and blended supplementary cementing materials — Physical requirements
(See Clauses 5.3 and 5.5.)

Property*	Type N	F	CI	CH	S	SF	SFI	Reference
Fineness, 45 µm, maximum % retained	34	34	34	34	20	10‡	10‡	CSA A3004-A3
Autoclave, maximum % expansion	0.8	0.8	0.8	0.8	0.5	0.2	0.2	CSA A3004-B5
Accelerated pozzolanic strength activity index, 7 days, minimum % of control	—	—	—	—	—	—	105	ASTM C 1240
Tendency to entrap air†	—	—	—	—	—	No visible foam	No visible foam	CSA A3004-A5

Strength Activity is optional

Table A.3
Supplementary cementing materials and blended supplementary cementing materials — Optional requirements
(See Clauses A.1 and A.4, and CSA A3004-E1.)

Property*	N	F	CI	CH	S	SF	SFI	Reference
Pozzolanic strength activity index,								
7 days, minimum % of control	—	—	—	—	—	105	—	ASTM C 1240
28 days, minimum % of control	75	75	75	75	—	—	—	ASTM C 311

ASTM C618/AASHTO M295

Effect of Non-Pozzolanic Ground Quartz Filler Material

Currently AASHTO M 295 requires that with a 20% replacement of cement by fly ash, mortar cubes must reach 75% of either the 7 or 28-day strengths of the 100% portland cement mortar cubes. This is represented as a Strength Activity Index (SAI) as described in ASTM C311.

As shown in Table 9, the AASHTO M 295 SAI requirement of 75% is flawed in that non-pozzolanic ground quartz silica fillers are able to meet this requirement at the current 20% cement replacement level. The SAI of a non-pozzolanic ground quartz silica flour, of approximately the same fineness as fly ash, was measured with three different portland cements, PC-1, PC-2 and PC-3, and this non-pozzolanic filler met the 75% strength level with all three cements, at a 20% replacement level. Therefore, due to the filler effect on nucleation of cement hydration, ground quartz would meet the requirements for a class F fly ash, despite not having any pozzolanic value. However, at a replacement level of 35% by volume, the non-pozzolanic filler would not have passed this limit.

Materials

		Class	CaO	SiO_2	Fe_2O_3	Al_2O_3	Sum of Oxides	Na_2O_e
Cement	PC-1		64	21	4.7	2.9	28	0.51
	PC-2		63	21	4.3	3.3	28	0.53
	PC-3		62	20	5.0	3.0	28	1.04
Fly Ashes	H	F	3.5	61	26	4.7	91	2.3
	M	F	7.2	60	17	5.0	82	4.2
	O	F	10	59	16	4.7	80	2.0
	Q	F	17	50	19	4.8	74	1.6
	U	C	22	39	19	7.0	66	2.2
	X	C	19	37	20	5.4	62	6.9
	ZA	C	27	33	17	5.7	55	4.0
	ZC	C	30	31	16	5.8	53	2.5
Filler	SiLEX		0.02	98.8	0.9	0.0	99.8	0.04

Effect of Quartz Filler (Silex 325)

Cement	Age (days)	Strength 100% Cement (MPa)	Strength 20% replacement with filler (MPa)	M295 SAI (%)	Strength 35% replacement with filler (MPa)	Old SAI (%)
PC-1	7	31.4	26.4	84	21.2	68
PC-2	7	29.6	23.5	79	18.2	62
PC-3	7	28.2	24.4	87	19.9	71
PC-1	28	39.4	33.2	84	27.2	69
PC-2	28	38.1	29.2	77	25.2	66
PC-3	28	35.4	30.0	85	22.8	64

All mixes with 20% filler pass 75% limit in C618, but not at 35% filler at 7 or 28d

Table 4.33. Strengths and SAI Using PC-4 using PC-4 with each of the eight CFA and the three inert fillers at 35% cement replacement.

	7 Day Strength 23 °C (psi)	7 day Strength 55 °C (psi)	28 day Strength 23 °C (psi)	SAI 7 day 23 °C (%)	SAI 7 day 55 °C (%)	SAI 28 day 23 °C (%)
Class F Fly Ash						
FA-H	3075	4685	5381	65.6	105.2	84.8
FA-M	3786	4975	6483	80.8	111.9	102.2
FA-O	3220	4700	5642	68.7	105.6	88.9
FA-Q	4496	6440	6947	95.9	144.8	109.5
Class C Fly Ash						
FA-U	4424	5511	7121	94.4	123.9	112.3
FA-X	4380	4946	5569	93.4	111.3	87.9
FA-ZA	4090	5395	6077	87.2	121.3	95.8
FA-ZC	4163	4380	6266	88.8	98.5	98.9
PC-4 Control	4685	4453	6338	-	-	-
INF-1	3263	3553	4119	69.7	80	65
INF-2	2799	2611	3553	59.6	58.7	56.1
INF-3	2843	2828	3655	60.6	63.5	57.7

At 35% replacement, fillers do not pass current C618 75% limit at 7 or 28d but fly ashes pass at 28d and 6/8 pass at 7d.

55C curing activates the fly ashes at 7d

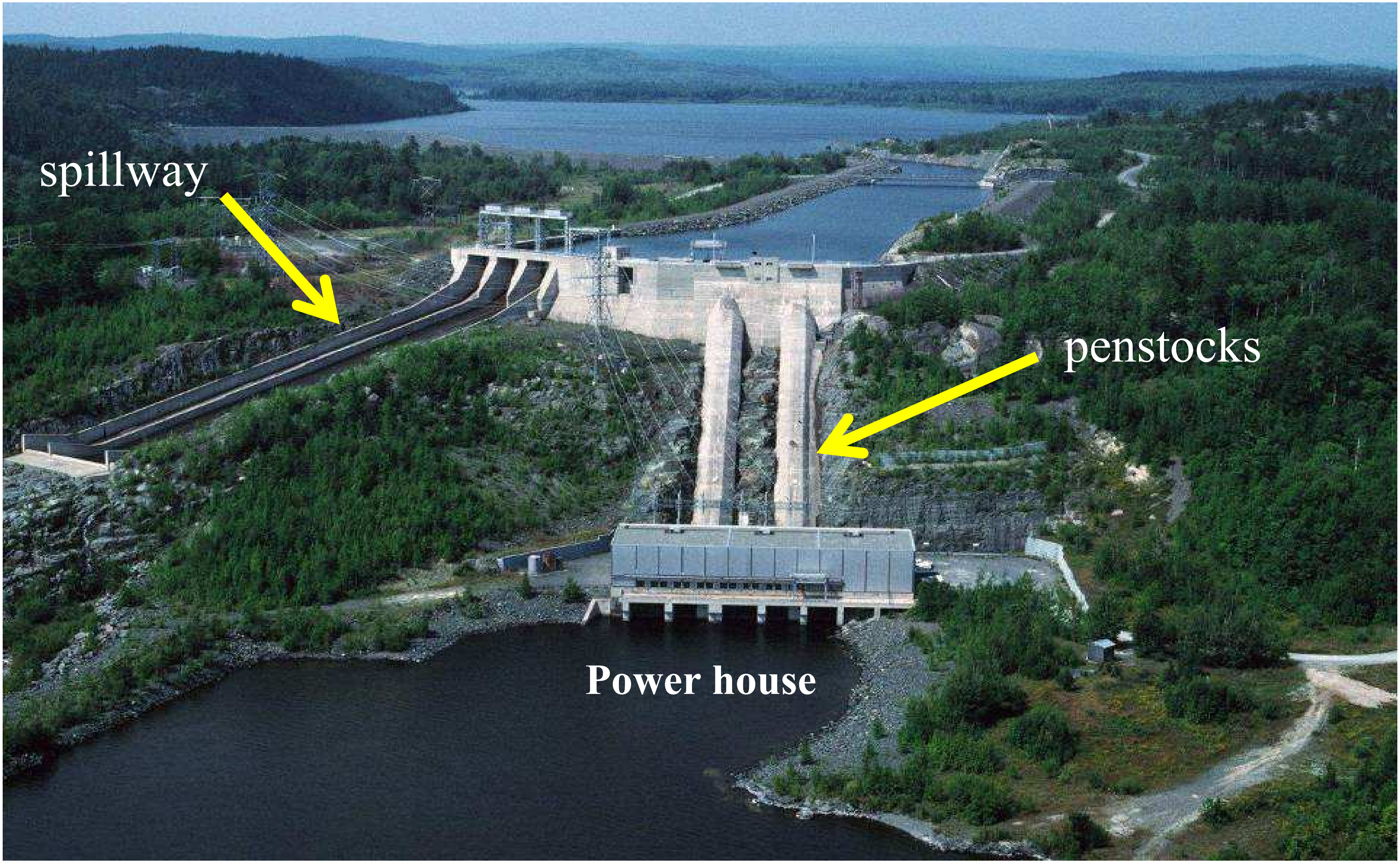
Ontario

- For over 25 years, most of the Class F ashes have been used for cement kiln feed or for waste stabilization.
- Cement companies have benefited from lower energy to react glassy fly ash in making clinker, as well as from using unburned carbon as fuel.
- Scrubber material has been used as calcium sulfate for cement.

Ontario

- Ontario has been shutting down its coal power plants and the last units will close in 2014.
- However, before that, the use of coal power for peak operations, as well as from low-NOx burners resulted in high-LOI ashes.

Lower Notch Dam, Montreal River, Northern Ontario



Lower Notch

- Lower Notch was built with ASR argillite-greywacke coarse aggregate which was crushed from the forebay excavation.
- Hydro tested the aggregate using C227 and old concrete prism test.
- Low-alkali cement, or 20, 30% class F fly ash were effective in mitigating expansion.
- The contractor was given the choice of using ash or LAPC, and chose fly ash.

Kenora
Thunder Bay
Timmins
U.S.A.
0 100 200 Mi
0 100 200 300 km
QUEBEC
North Bay
LAKE HURON
Toronto
LAKE ONTARIO
U.S.A.
Windsor
LAKE ERIE
ALKALI-SILICA REACTIVE CHERT IN GRAVEL DEPOSITS AND IRON MINE WASTE
ALKALI-SILICA & SILICATE REACTIVE ARGILLITE GREYWACKE & SANDSTONE IN GRAVEL DEPOSITS
ALKALI-SILICA REACTIVE CHERTY LIMESTONE AND ALKALI-CARBONATE REACTIVE DOLOMITIC LIMESTONE IN QUARRIES
ALKALI-SILICA REACTIVE CHERT IN GRAVEL DEPOSITS AND QUARRIES

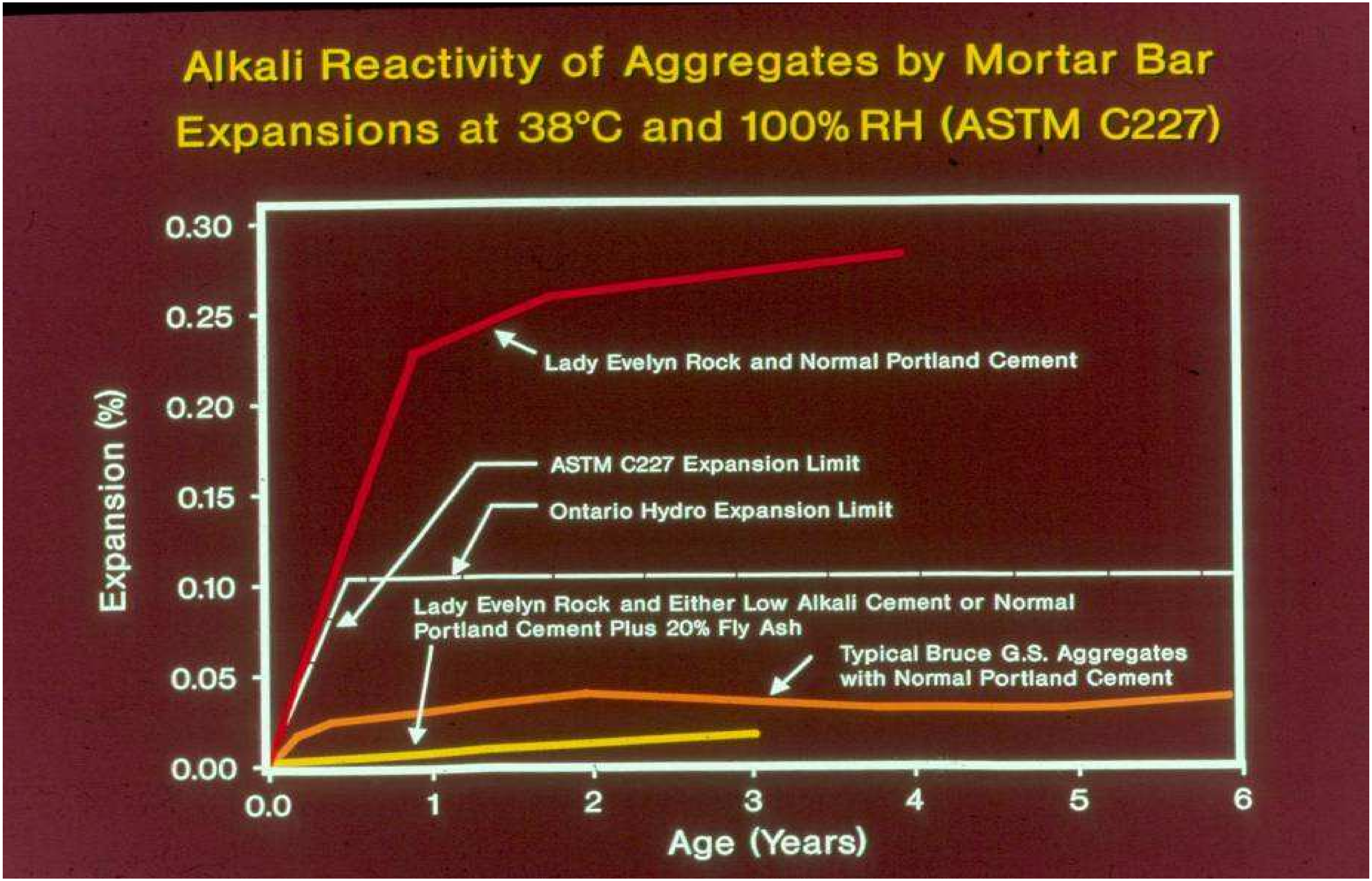
COMPARISON OF SAND-GRAVEL SAMPLES FROM THE CANADIAN SHIELD

1967
Hydro
Report

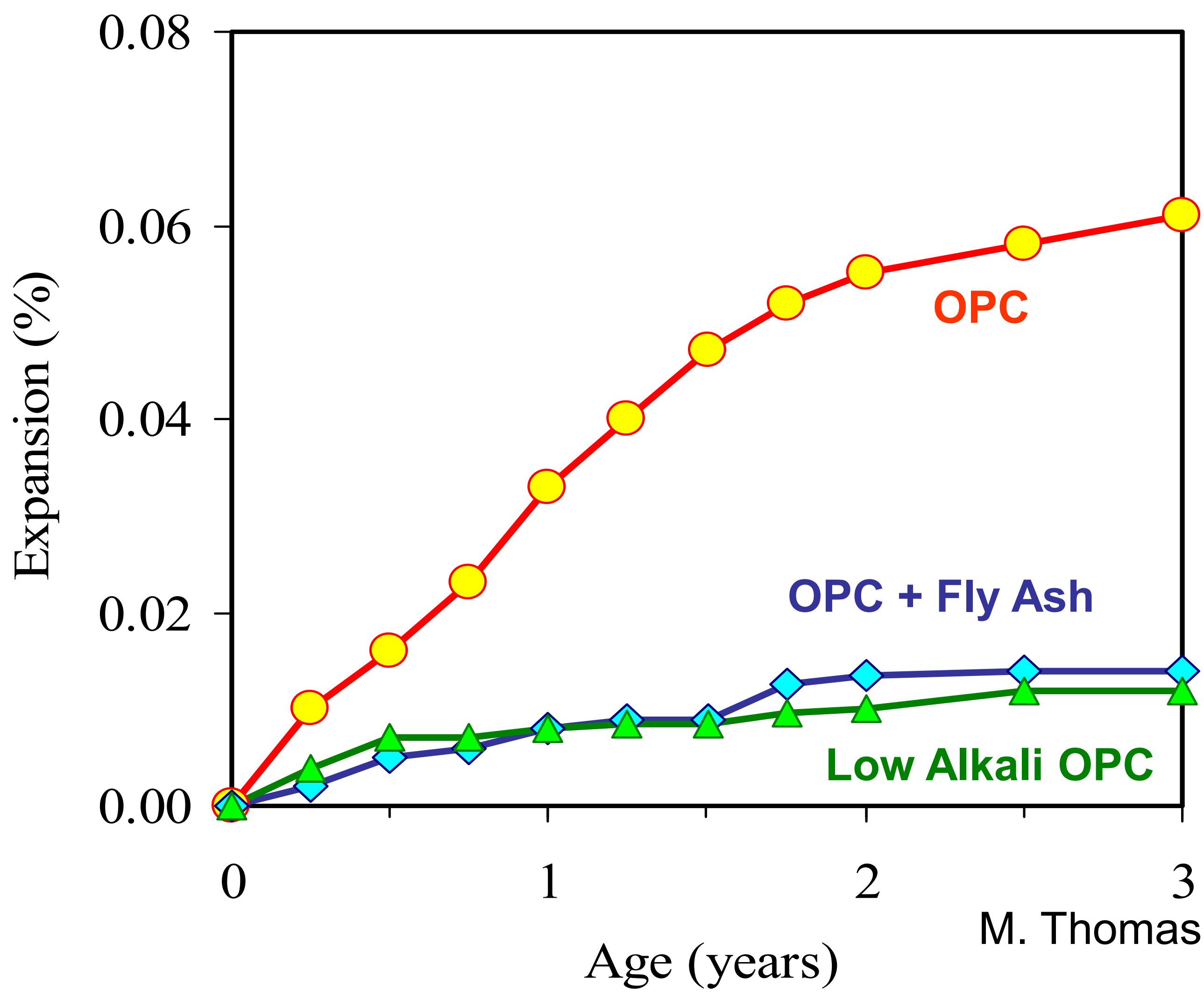
L. Dolar-Mantuani

Location (Gravel	Lower Notch (A)		Red Rock	Aubrey Falls	Silver Falls
		Composition of gravel aggregate			
Intrusive rocks and gneisses	4.8	10.4	15.3	78.2	51.8
Diabase	0.5	2.7	26.2	14.2	33.5
Sedimentary rocks (sandstones, argillite)	94.5	82.7	57.1	0.2	6.9

(A) - Crushed drill core

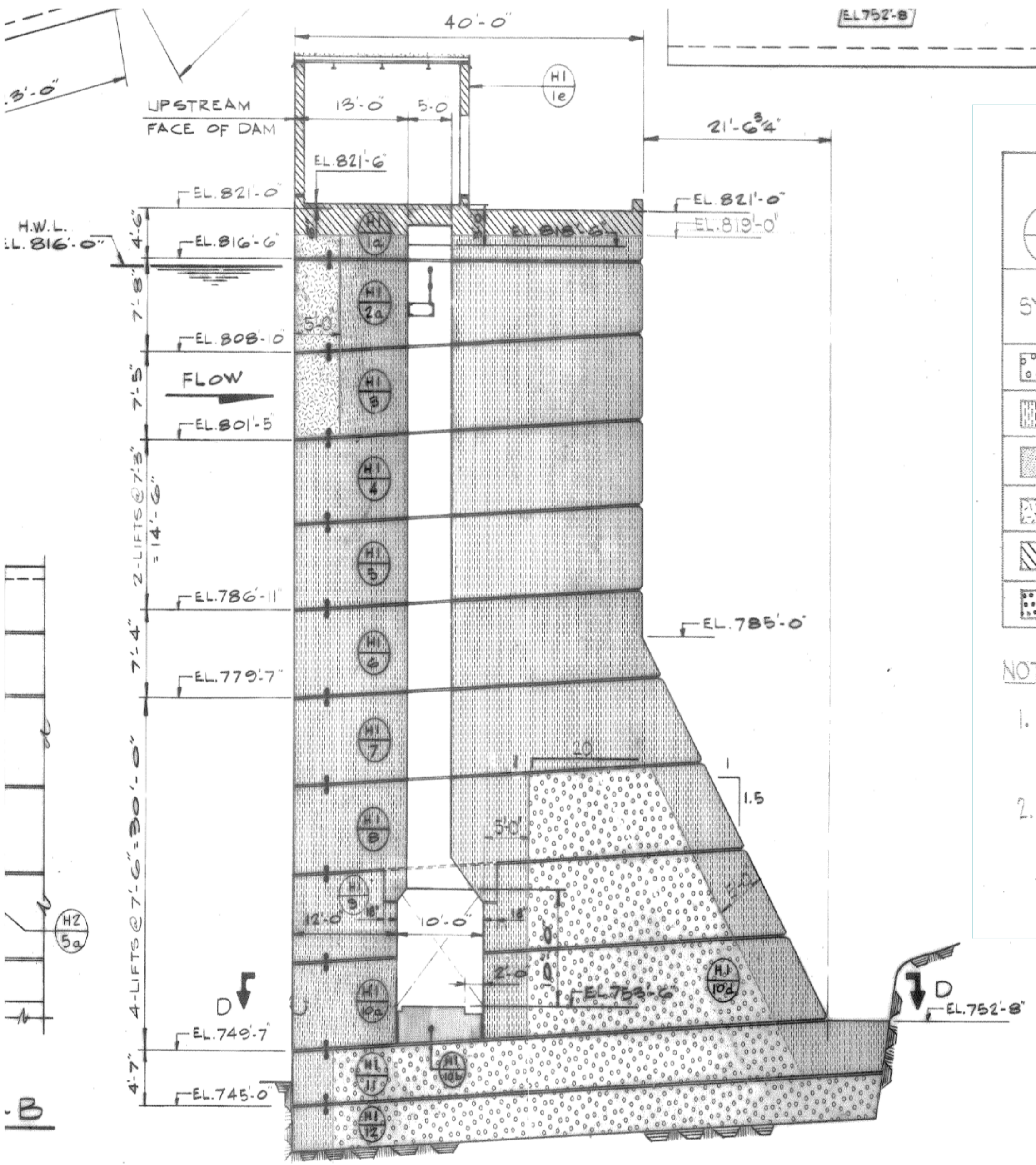

Alkali Reactivity of Aggregates by Mortar Bar
Expansions at 38°C and 100% RH (ASTM C227)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Expansion (%)
Lady Evelyn Rock and Normal Portland Cement
ASTM C227 Expansion Limit
Ontario Hydro Expansion Limit
Lady Evelyn Rock and Either Low Alkali Cement or Normal Portland Cement Plus 20% Fly Ash
Typical Bruce G.S. Aggregates with Normal Portland Cement
0.0
1
2
3
4
5
6
Age (Years)

Concrete Expansions



Greywacke coarse aggregate
and pit sand from Lower Notch

Excess Aggregate stockpiles



LEGEND

(H1/11) CONCRETE POUR NUMBER

SYMBOLS	CLASS OF CONCRETE	MAX. SIZE OF AGGR. IN INCHES	MINIMUM COMPRESSIVE STRENGTH P.S.I.	DAYS	REFERENCE
	1	3"	2,000	90	SEE NOTE-2
	2	3"	3,000	90	SEE NOTE-2
	3	1 1/2"	3,000	28	SEE NOTE-2
	3a	1 1/2"	3,000	28	SEE NOTES 1 & 2
	4	3/4"	3,000	28	SEE NOTE-2
	6	1 1/2"	4,000	28	SEE NOTE-2

NOTES

1. CLASS "3a" SIMILAR TO CLASS "3" EXCEPT THAT WATER CEMENT RATIO SHALL NOT EXCEED 0.50.
2. FLY ASH CONTENT FOR ALL MIXES EXCEPT CLASS 2 SHALL NOT EXCEED 20% OF THE TOTAL WEIGHT OF CEMENTING MATERIAL. FLY ASH CONTENT FOR CLASS 2 SHALL NOT EXCEED 30%.

Some concrete mixes had 20mm, 38mm, and 75mm aggregate

Upstream piers/gates

Upstream blockout

South Wing Wall

Spillway Piers

100mm cores ~2m long

New Brunswick

- It is planned to replace the ASR-affected Mactaquac power dam by 2030 and use the same aggregate. It is planned to use High-volume fly ash (50-60%) to prevent ASR.
- Landfilled fly ash may be used in case existing coal plants are no longer running, or if the ash has changed.
- In 2010, 10 foot cubes were cast with different levels of fly ash to determine ASR mitigation (M. Thomas)

Mactaquac Generating Station (1964-68)

- Located on the St. John River ~ 20 km west of Fredericton
- Second largest hydroelectric plant in Atlantic Canada
- Generating capacity = 672MW.
- Construction 1964 - 1968
- After ~10 years the concrete structures started to exhibit distress which was later (1985) attributed to ASR.
- Since 1985, various remedial measures have been undertaken to mitigate the effects of concrete expansion

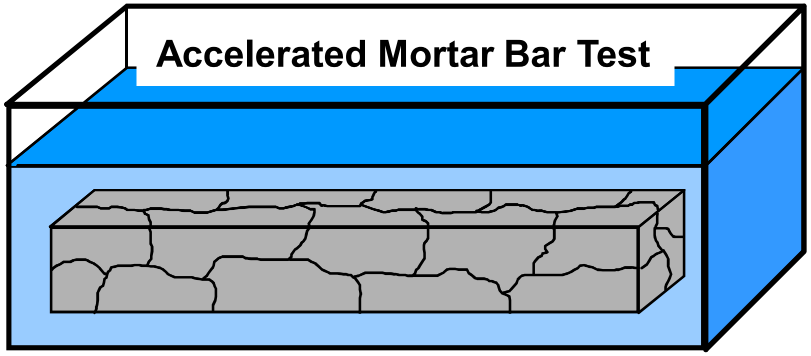
Concrete Mixes for Demonstration Project

- Control mix (0% fly ash), 30%, 40% & 50% processed fly ash and 50% reclaimed fly ash from landfill

  Prediction: 30% fly ash will just fail, 40% will just pass, 50% includes safety margin and will serve as a demonstration that long-term properties of concrete with 50% fly ash are acceptable

- Cement content: 420 kg/m^3
- Cement alkalis: highest available – boosted to 1.25% Na_2Oe
- W/CM: adjusted to give required slump (75 to 100 mm)
- Springhill used as a surrogate Mactaquac aggregate

Methods of Evaluation



Accelerated Mortar Bar Test

Blocks on UNB Exposure Site

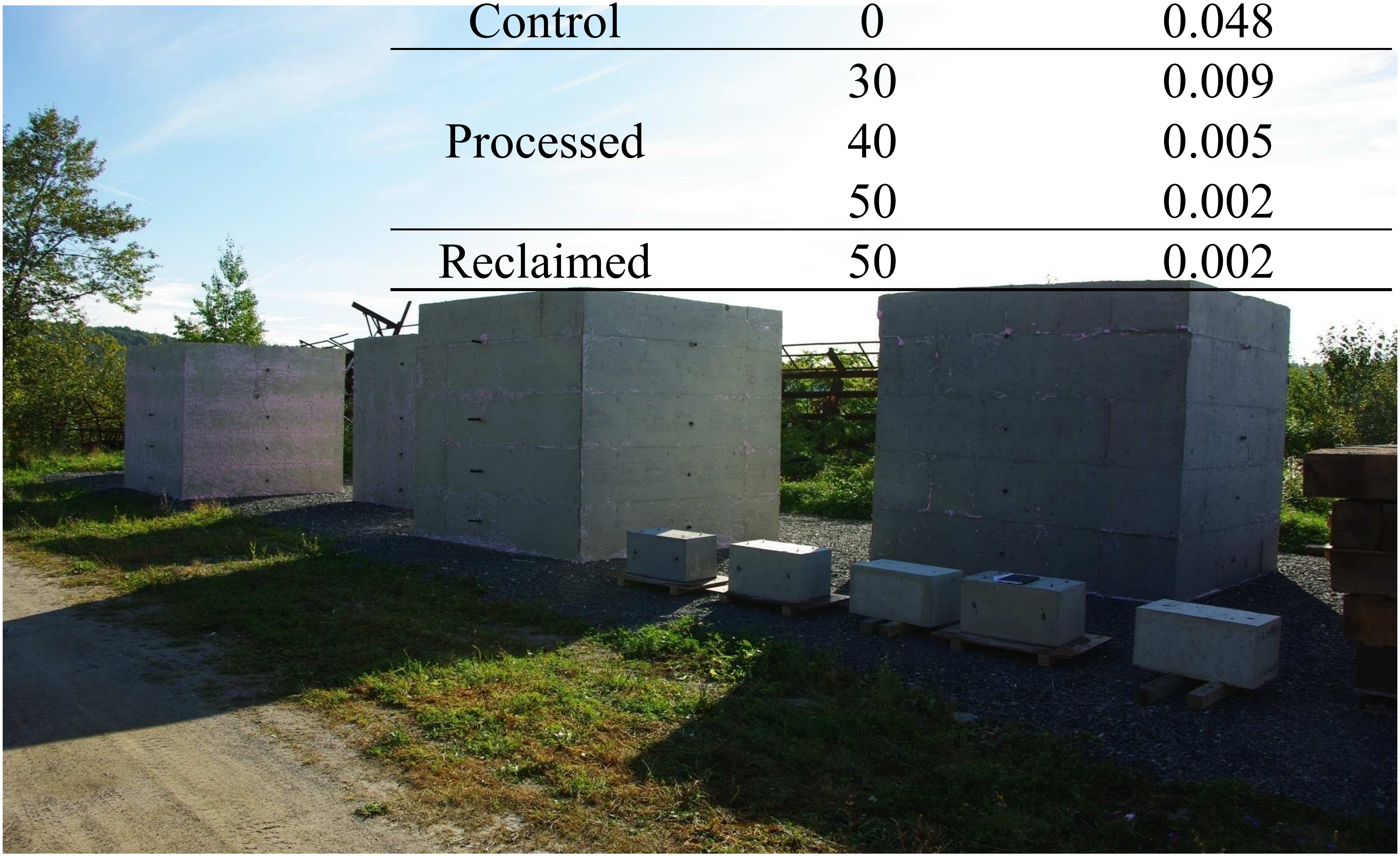
Concrete Prism Test

3.05-m Cubes at Mactaquac

Blocks in the inspection gallery at Mactaquac

3-Year Results

Block	Fly Ash (%)	Exp (%)
Control	0	0.048
Processed	30	0.009
	40	0.005
	50	0.002
Reclaimed	50	0.002



Europe

- Fly Ash is used in blended cements in EN197-1, most commonly as:
- CEMIIA-V (6-20% siliceous ash)
- CEMIIB-V (21-35% siliceous ash)
- CEMIIA-W(6-20% calcareous ash)
- CEMIIB-W(21-35% calcareous ash)

- Can also have up to 55% ash in CEMIV-B cements

Europe

- **The EN206 Concrete standard allows fly ash additions that meet EN 450.**
- **Activity index** (in percent) of the compressive strength of standard mortar bars, prepared with 75 % test cement plus 25 % fly ash by mass, to the compressive strength of standard mortar bars prepared with 100 % test cement, when tested at the same age
- Min. activity Indices: 28d =75%; 90d = 85%

NOTE The result of the activity index tests gives no direct information on the strength contribution of fly ash in concrete, nor is the use of the fly ash limited to the mixing ratio used in these tests.

EN450 Co-combustion ash

- Fly ash from co-combustion as defined in 3.2 is obtained from pulverised coal fired simultaneously with at least one co-combustion material as listed in Table 1. The minimum percentage, by dry mass, of coal shall be not less than 60 % or 50 % if the co-combustion material is only from green wood.
- The maximum proportion of ash derived from co-combustion materials shall not be greater than 30 % by dry mass.

EN450

Table 1 — Types of co-combustion materials

1	Solid Bio Fuels conforming to CEN/TS 14588:2003 including animal husbandry residues as defined in 4.3 and excluding waste wood as defined in 4.40, 4.107 and 4.136.
2	Animal meal (meat and bone meal)
3	Municipal sewage sludge
4	Paper sludge
5	Petroleum coke
6	Virtually ash free liquid and gaseous fuels

Japan

- JIS A 6201 (Fly ash for use in concrete)
- The silicon dioxide content of fly ash is required to be not less than 45% regardless of the type of fly ash.

- The ignition loss of fly ash to be used shall be within certain tolerances from the value at the time of establishing or modifying the proportions of concrete.
- When used with an air-entraining admixture or air-entraining and water-reducing admixture for general use, Type I and Type II fly ashes shall have an ignition loss determined at the time of proportioning/re-proportioning ±0.5 and ±1.0 percentage points, respectively.
- When using an air-entraining admixture for use with fly ash, the tolerances may be widened to ±1.0 and ±1.5 percentage points for Type I and Type II, respectively.

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Australia

AS 3582.1 Supplementary cementitious materials for use with portland cement Part 1 Fly ash.

Summary

- Coal fly ash is changing: co-combustion is becoming more common.
- Hg-control has variable impacts on Air-entrainment.
- The current Strength Activity test limits do not distinguish ash from filler.
- Ash CaO content has a direct link to ASR and sulfate resistance.
- Standards need to adapt.