Alkali-aggregate Reactions in Concrete

- A review -

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UNIVERSITÉ LAVAL

IBRACON

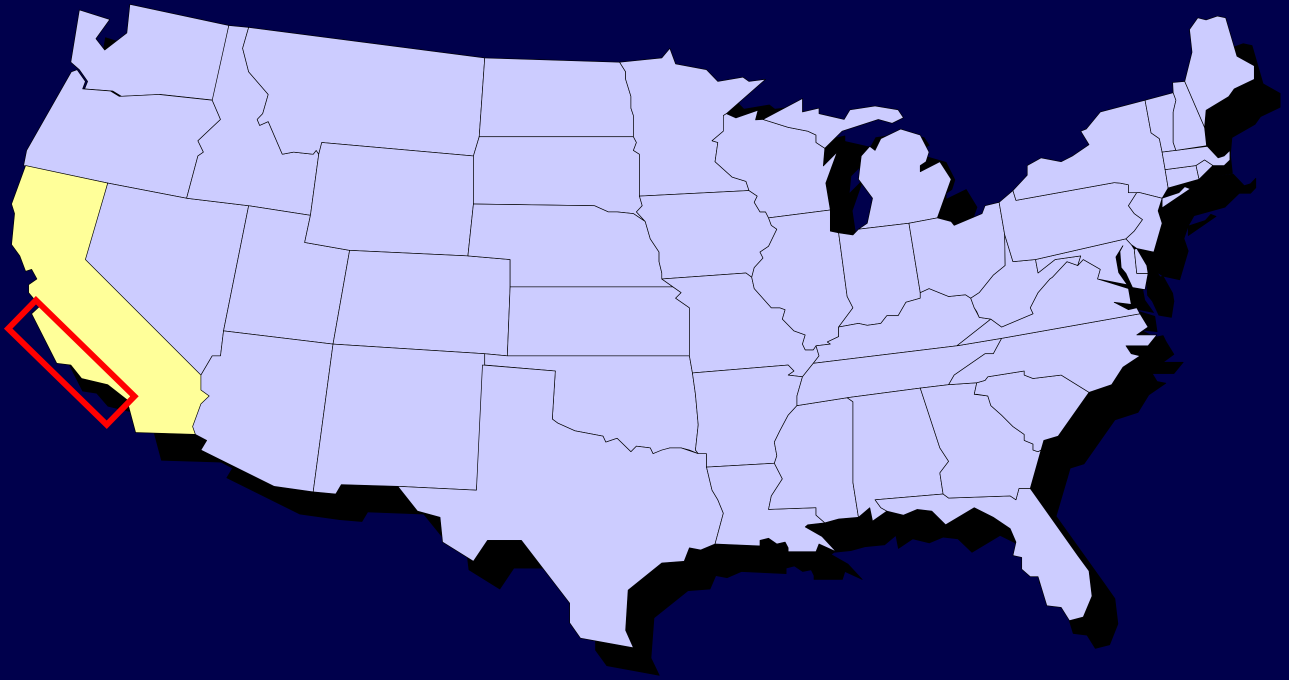
Fortaleza 2010

52º CONGRESSO BRASILEIRO DO CONCRETO

AAR → one of many deleterious mechanisms affecting the durability of concrete

(Mehta and Monteiro 1999)

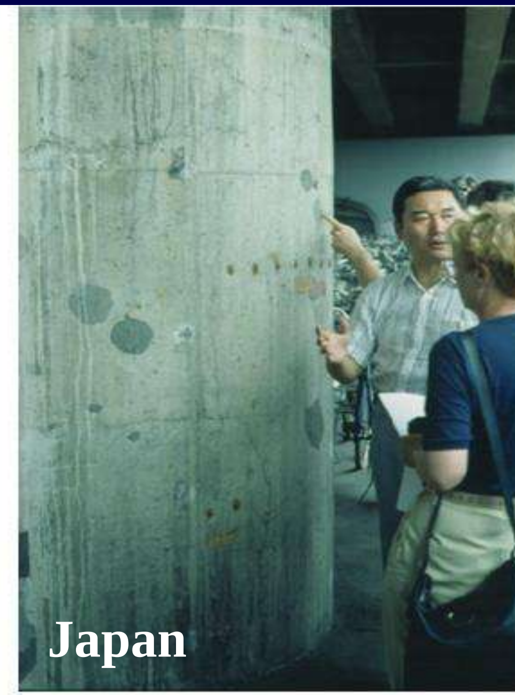
First report of AAR

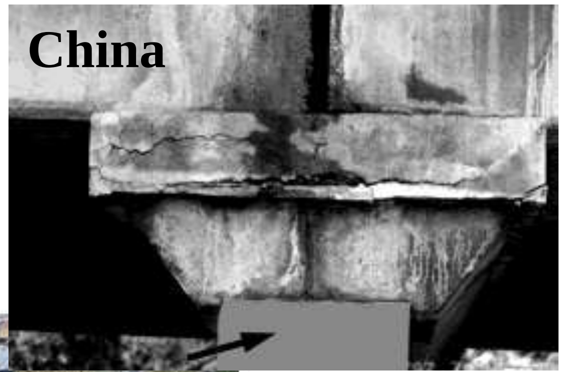


- 1930’s in the Monterey and Los Angeles counties (Californie)
- Thomas Stanton, Caltrans

Structures affected by AAR all around the world


South Africa



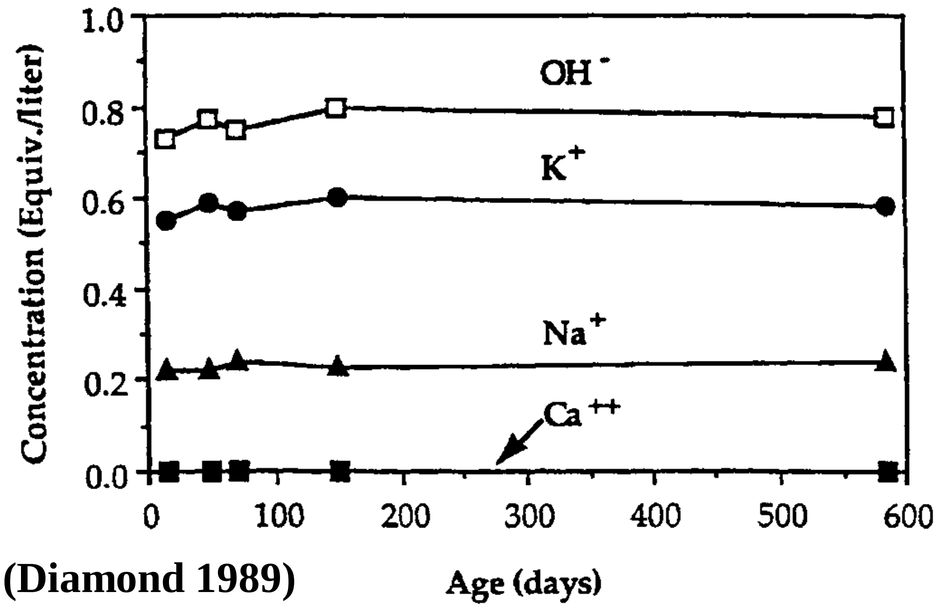


13 international conferences since 1974

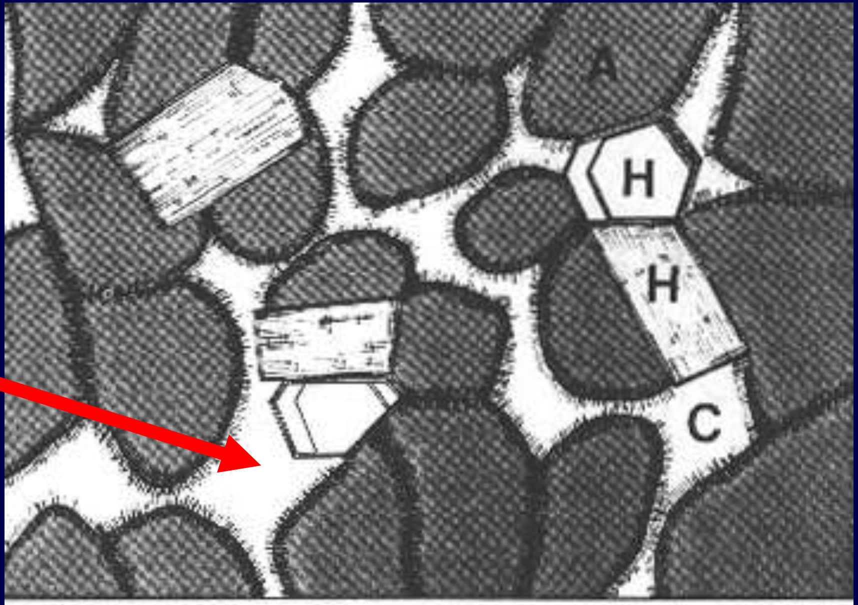
Thousands of papers, reports, specifications, guidelines

Pore fluid in concrete:

- Mainly composed of K+, Na+ and OH- → pH ≥ 12.4
- Some mineral phases unstable in ↑ pH conditions → alkali-aggregate reactions



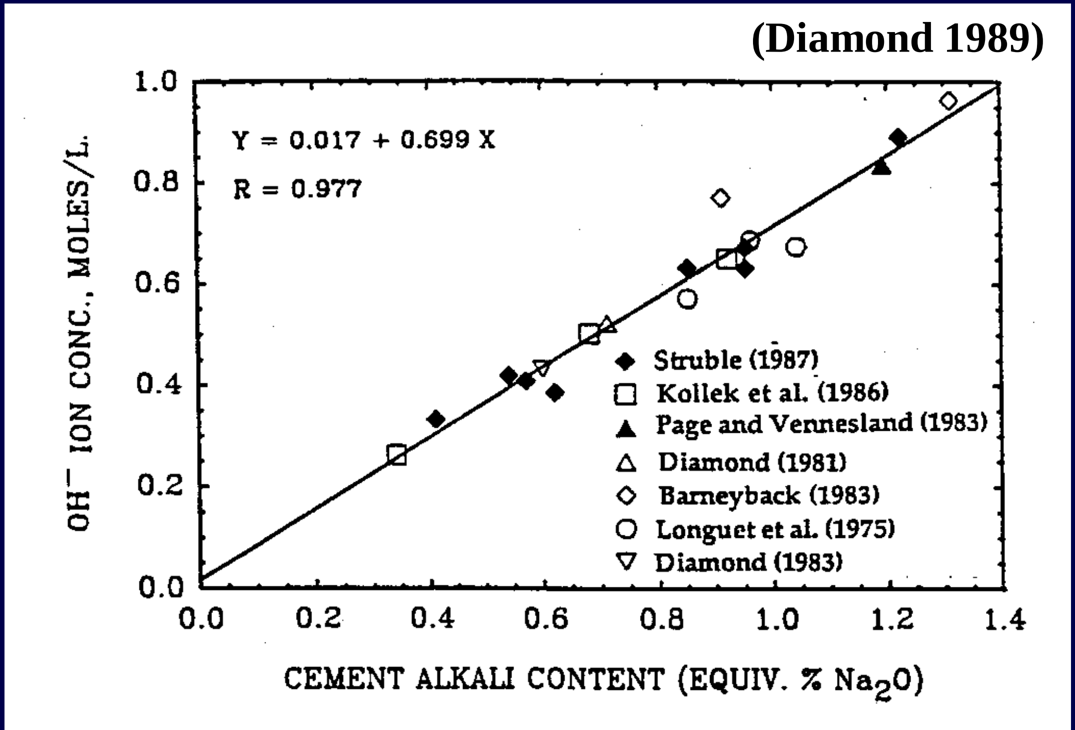
(Diamond 1989)

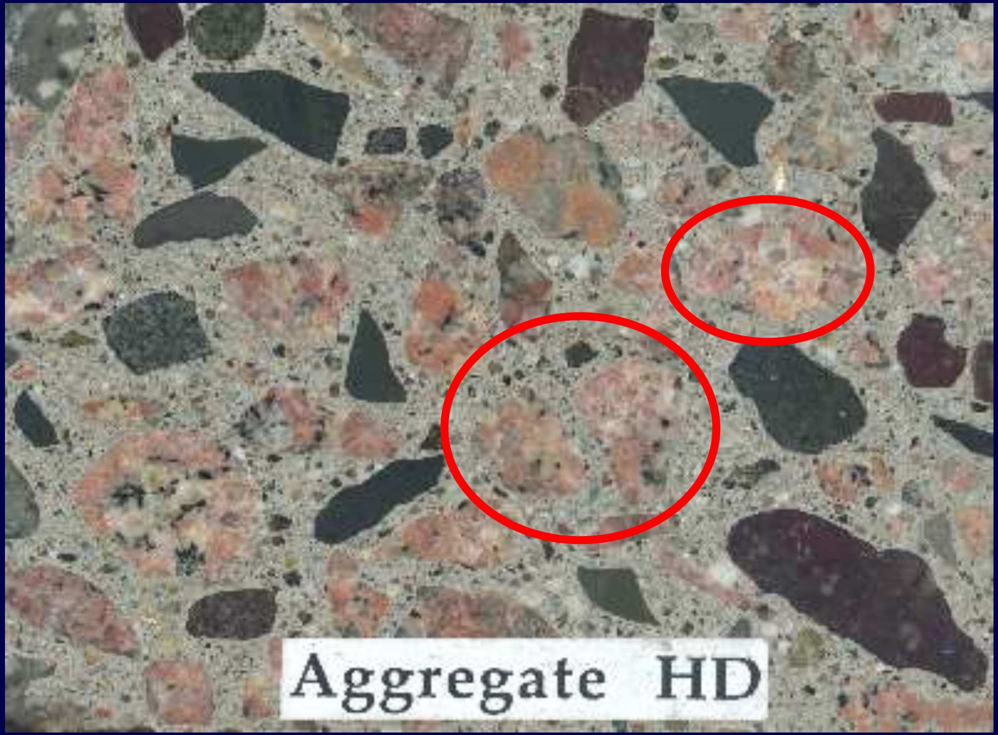


(Mehta and Monteiro 1999)

- Alkalis from ≠ sources:
  - Cement (mainly)
  - Aggregates (~ long term)
  - Other cementitious materials
  - Chemical admixtures
  - sea water, deicing chemicals

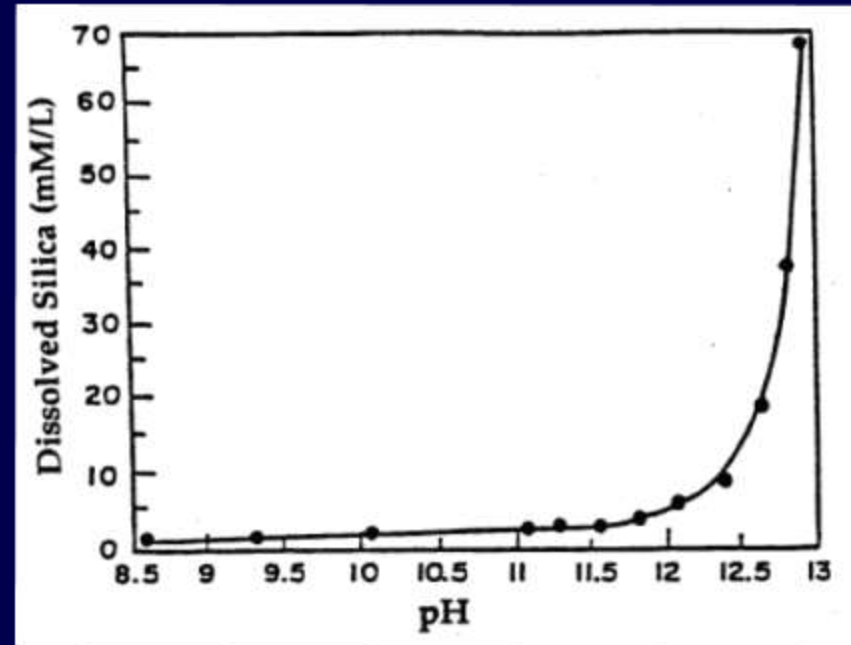
(Diamond 1989)

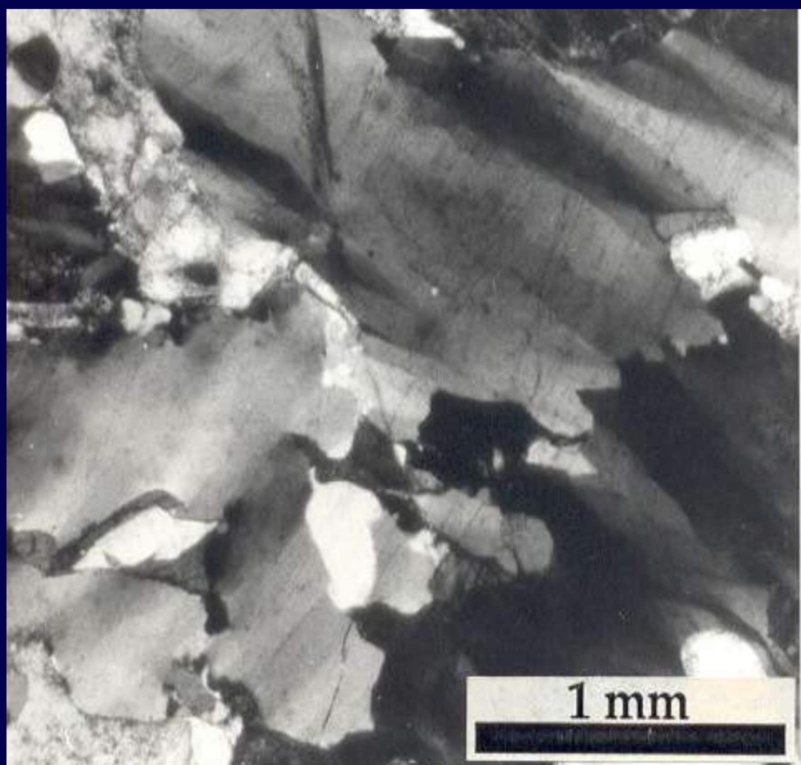




Alkali-Silica Reaction

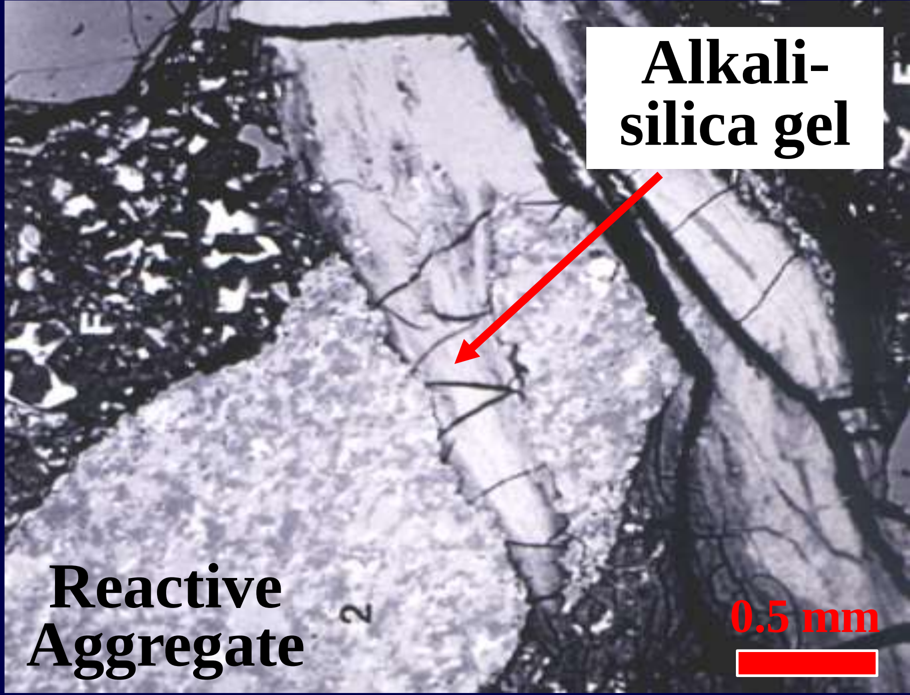
- Most common form of AAR
- Reaction between concrete pore fluid (↑ pH) and <u>siliceous phases</u> from aggregates

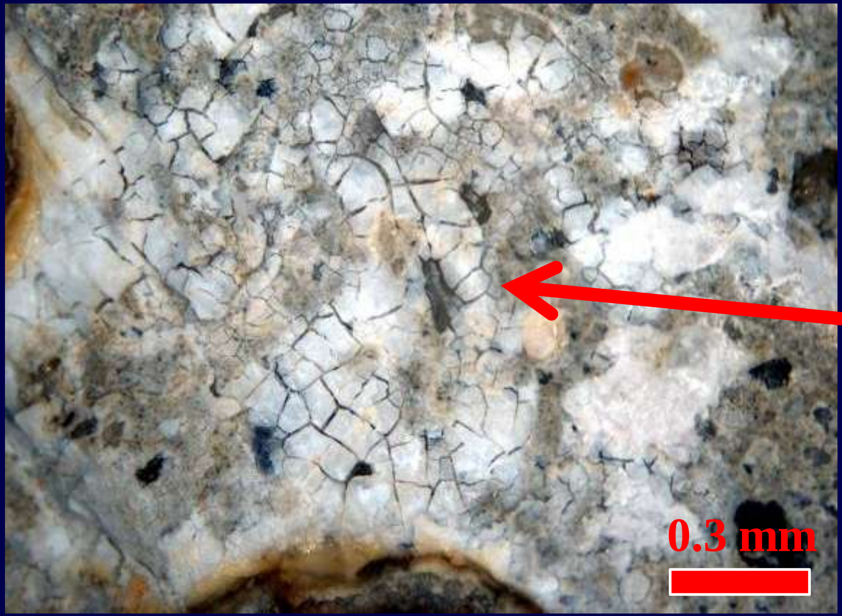


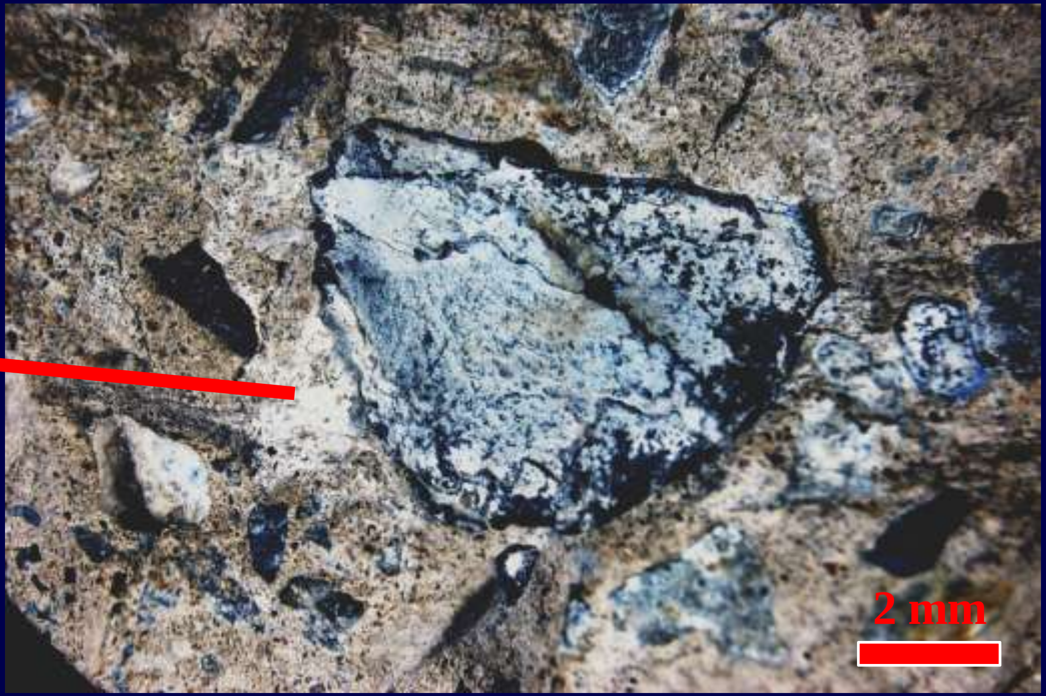


Alkali-Silica Reaction

- Deleterious reaction produces secondary reaction product → alkali-silica gel
- Gel swells in the presence of moisture

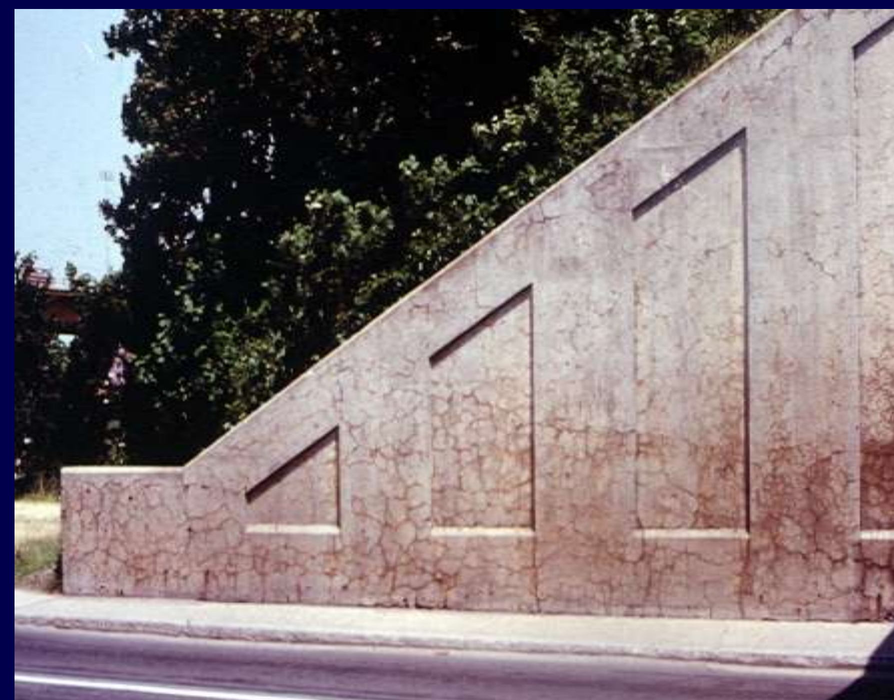






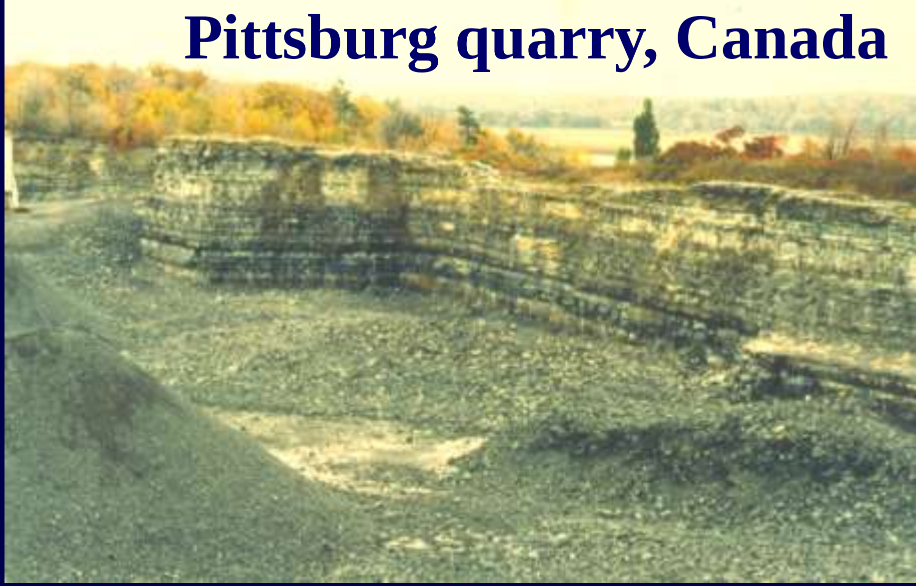
Alkali-Silica Reaction

- **Internal expansion forces → cracking and distress of concrete**



Alkali-Carbonate Reaction

- Limited cases from Canada, USA, China, Austria
- "Classical" ACR in Canada: argillaceous dolomitic limestone



Time for Distress Due to AAR

- Less than 2 to more than 25 years
- Depends on various factors

Reactive Material
in the aggregates

Sufficient
Alkali

Sufficient
Moisture

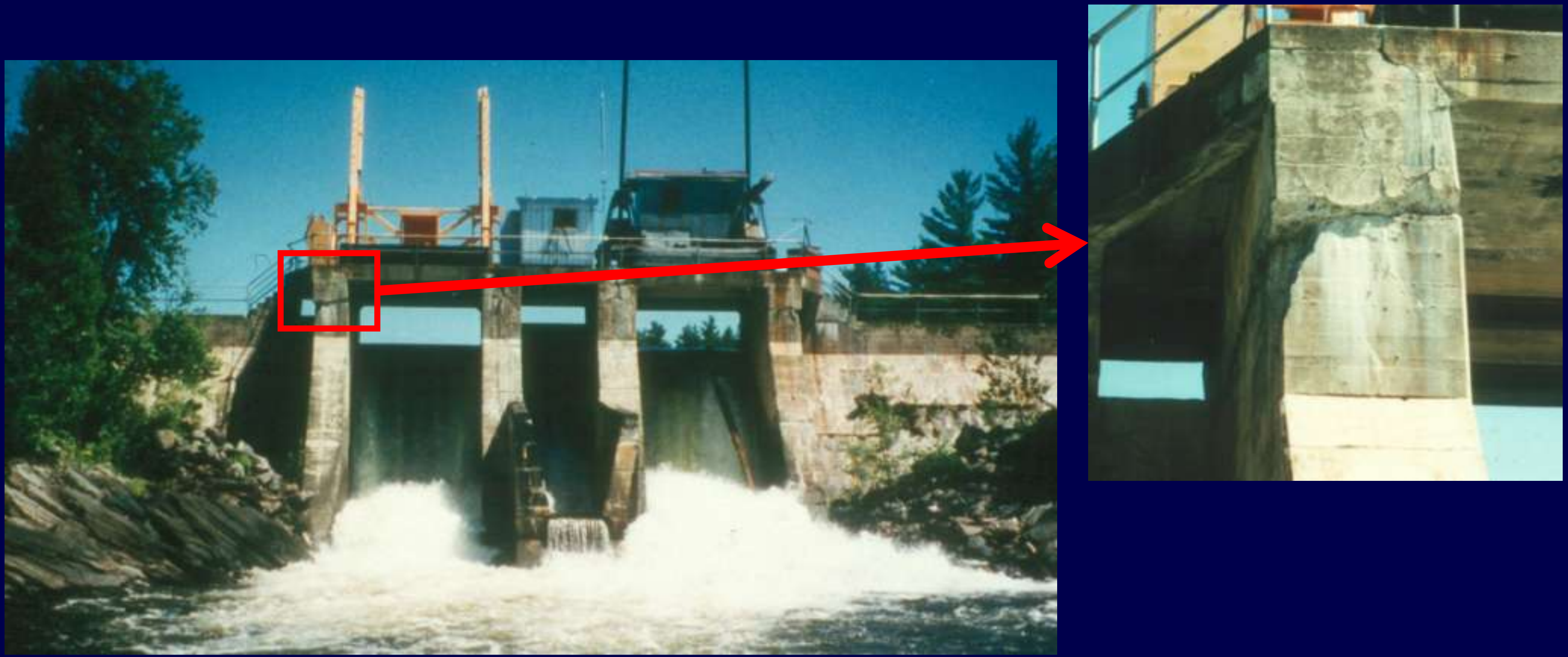
How serious is the problem ??

AAR – the Problem

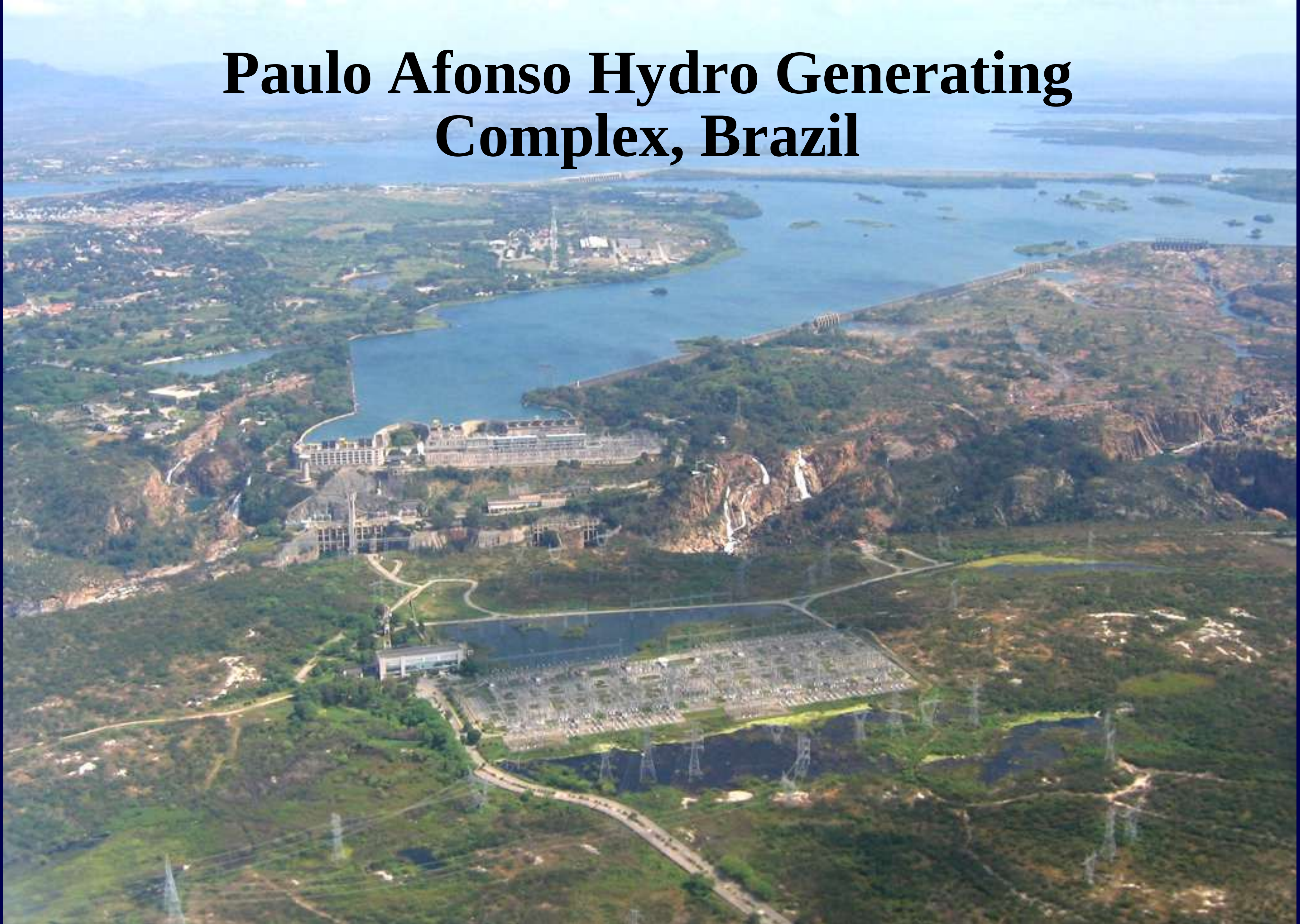
- Very few cases of structures demolished essentially because of AAR

AAR – the Problem

- Extensive cracking → durability issues (rebar corrosion)
- Differential expansion and movements in critical structures (bridges, dams) → operational issues → repairs and $$$$



Paulo Afonso Hydro Generating Complex, Brazil




CENTIMETRES
INCHES

ASR Damage Channel Islands - USA

Built in 1989 - $14M to Rebuild
(Photos c. 1993, courtesy ANG)

Sherman (2006)

AAR Must be Prevented !!

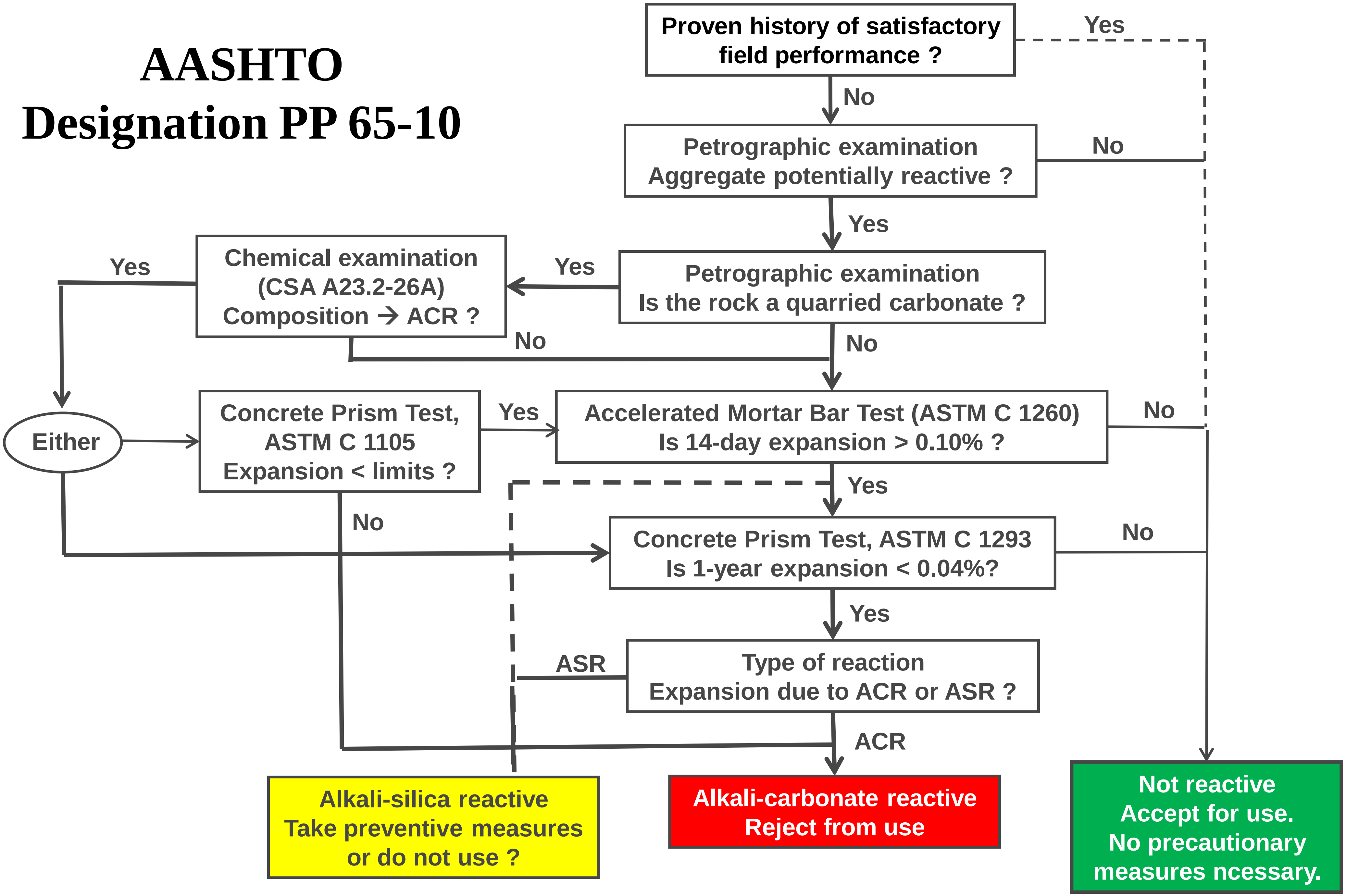
In 2010, there is no excuse to construct a structure at risk of AAR !

1. Properly recognize the potential alkali-reactivity of aggregate
2. Select and use appropriate preventive action(s) in the presence of reactive aggregates

Lab Testing

- ↑ T°
- ↑ alkali content
- ↓ particle size

AASHTO Designation PP 65-10



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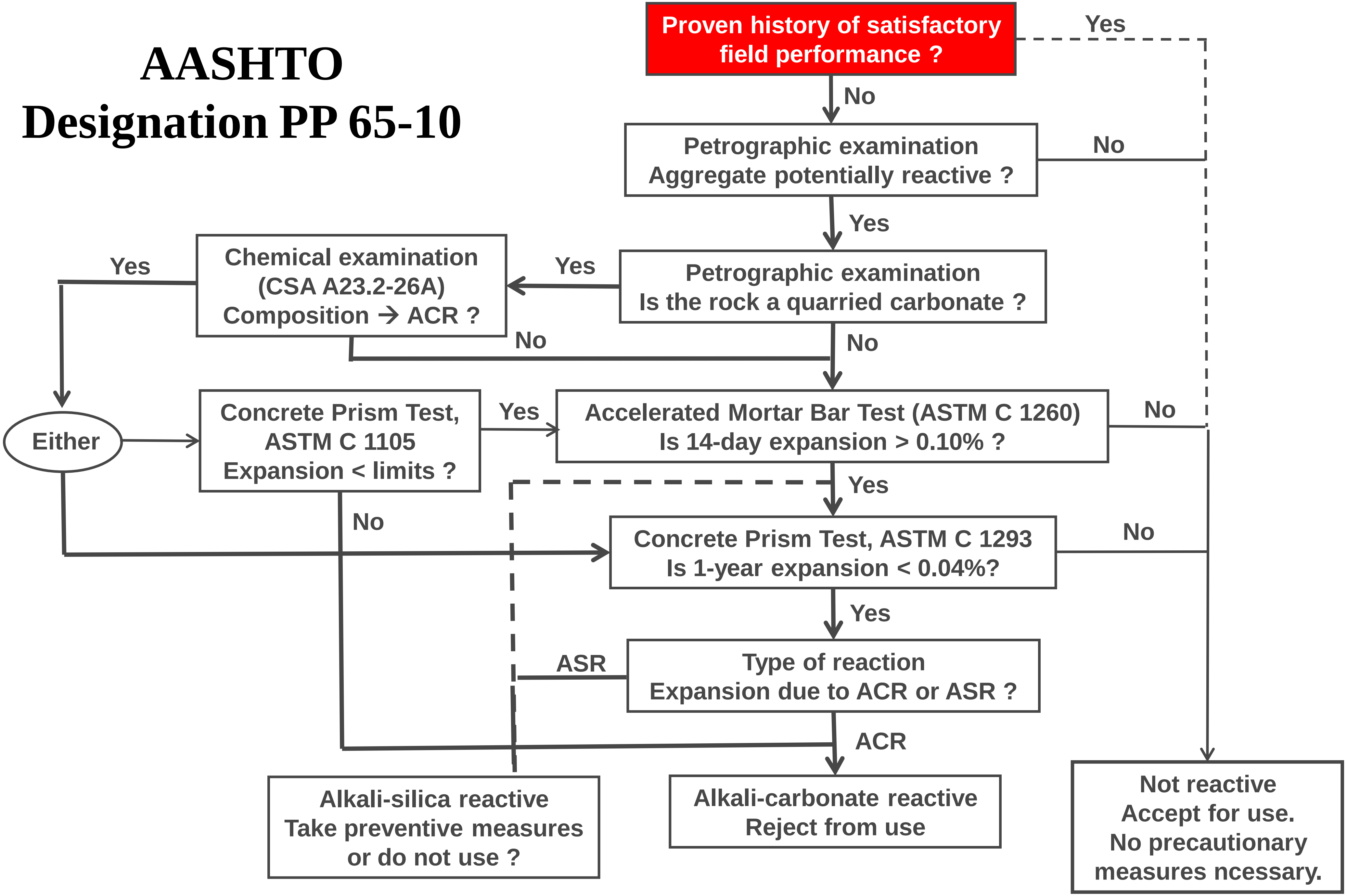
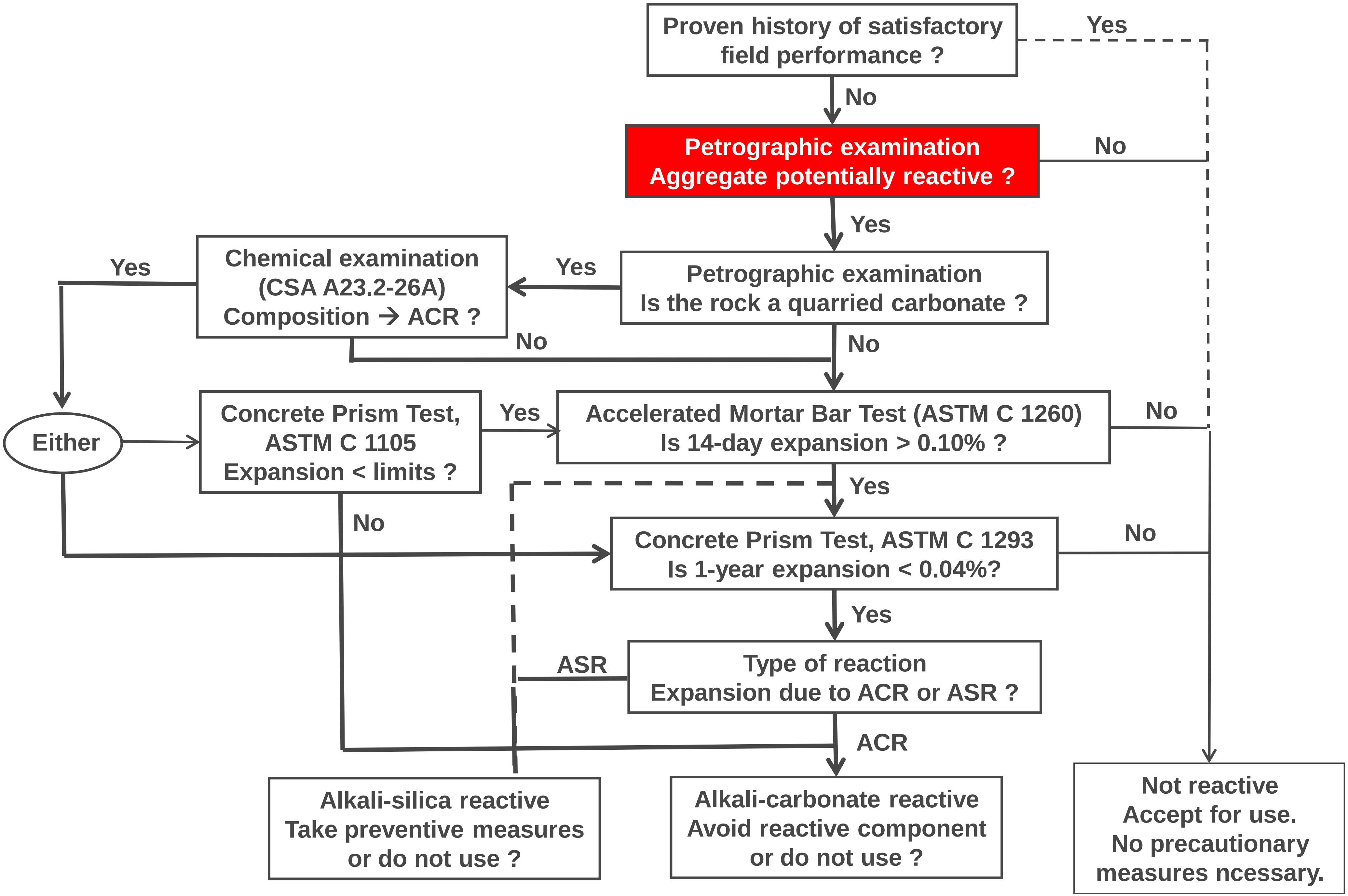


Field Performance Survey of AAR

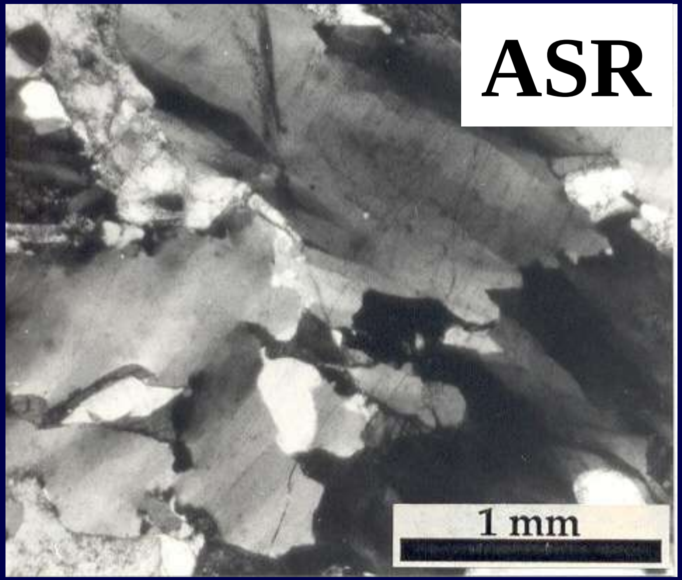
- Structure > 10 years old
- Structure incorporating high alkali levels
- Structure exposed to severe conditions (moisture)
- No “preventive measures” used (pozzolans, etc.)

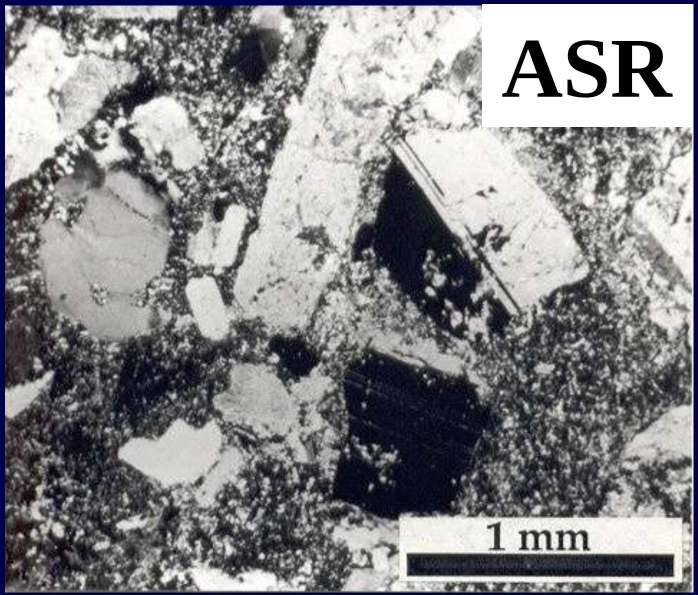


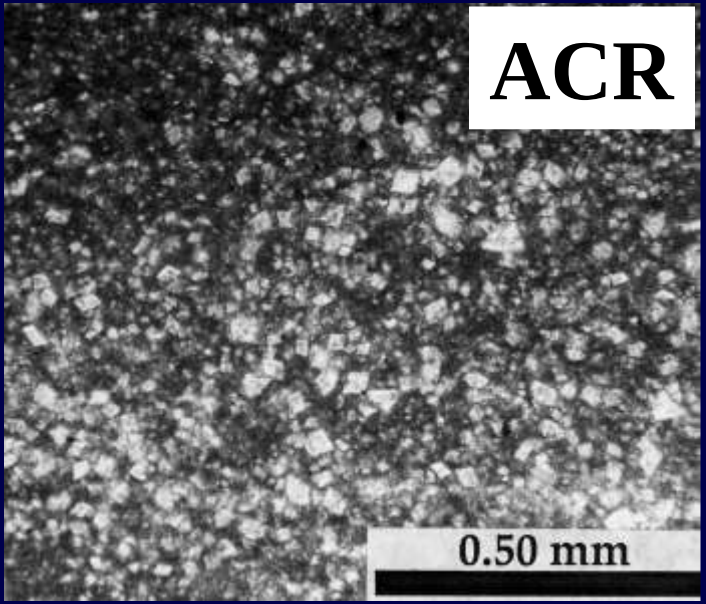
Proven history of satisfactory field performance ?
Yes
No
Petrographic examination Aggregate potentially reactive ?
No
Yes
Chemical examination (CSA A23.2-26A) Composition → ACR ?
Yes
Yes
Petrographic examination Is the rock a quarried carbonate ?
No
No
Either
Concrete Prism Test, ASTM C 1105 Expansion < limits ?
Yes
Accelerated Mortar Bar Test (ASTM C 1260) Is 14-day expansion > 0.10% ?
No
Yes
No
Concrete Prism Test, ASTM C 1293 Is 1-year expansion < 0.04%?
No
Yes
ASR
Type of reaction Expansion due to ACR or ASR ?
ACR
Alkali-silica reactive Take preventive measures or do not use ?
Alkali-carbonate reactive Avoid reactive component or do not use ?
Not reactive Accept for use. No precautionary measures ncessary.

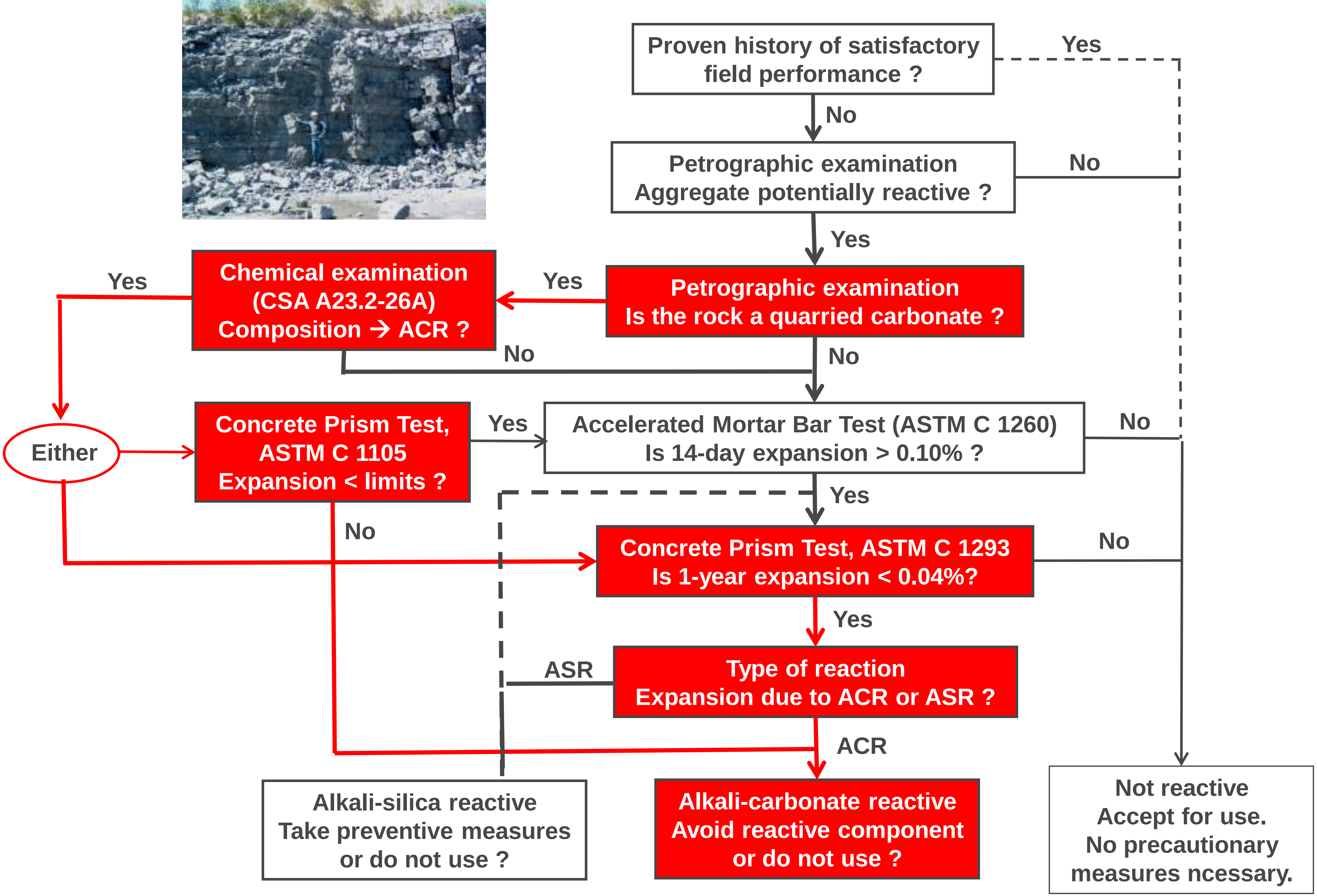
Petrographic Examination

- **Essential step:**
  - **Nature of aggregate (ACR, ASR)**
  - **Select best test to perform**
- **Risky to accept/reject aggregates based on petrographic examination only.**









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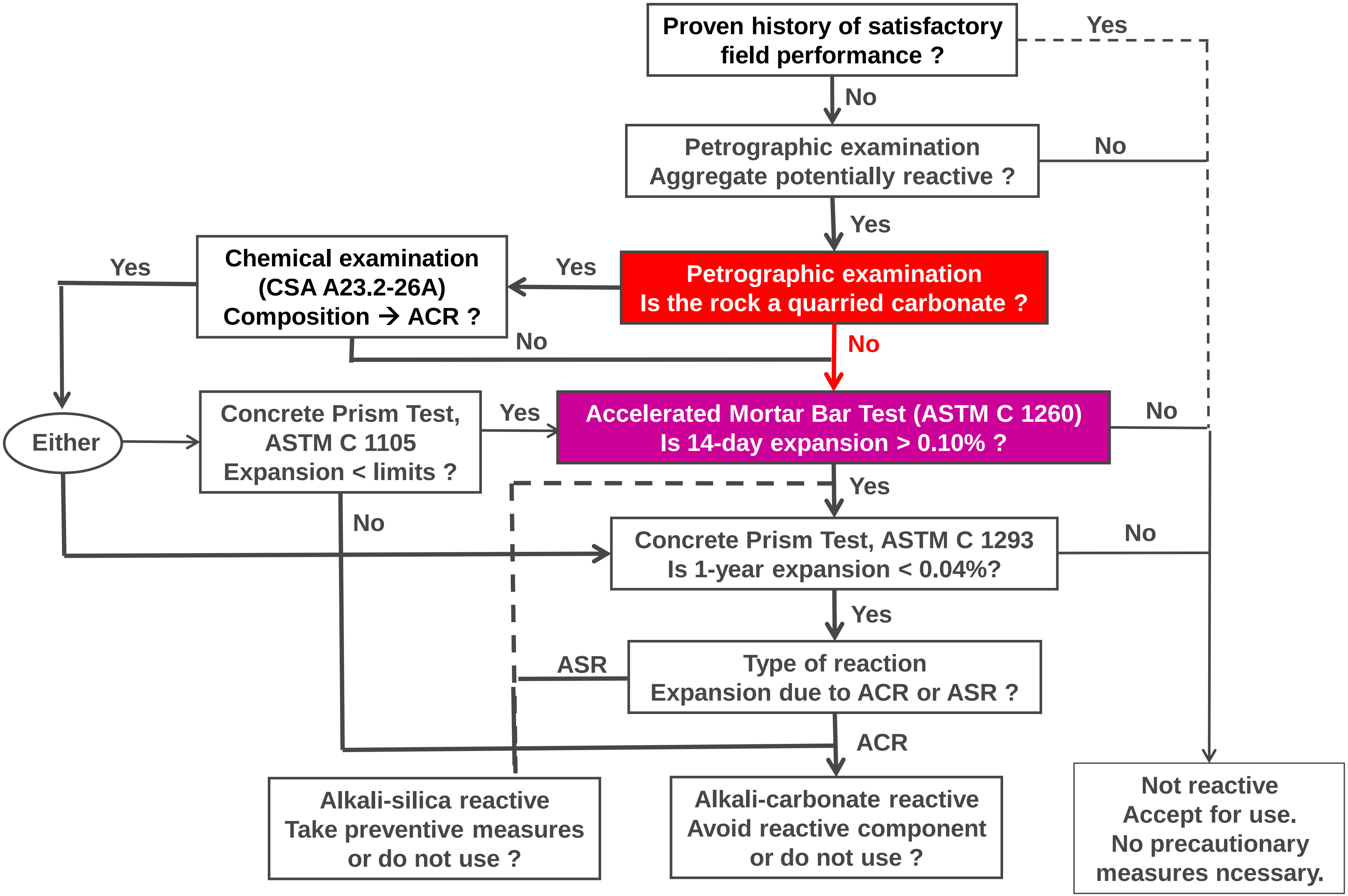
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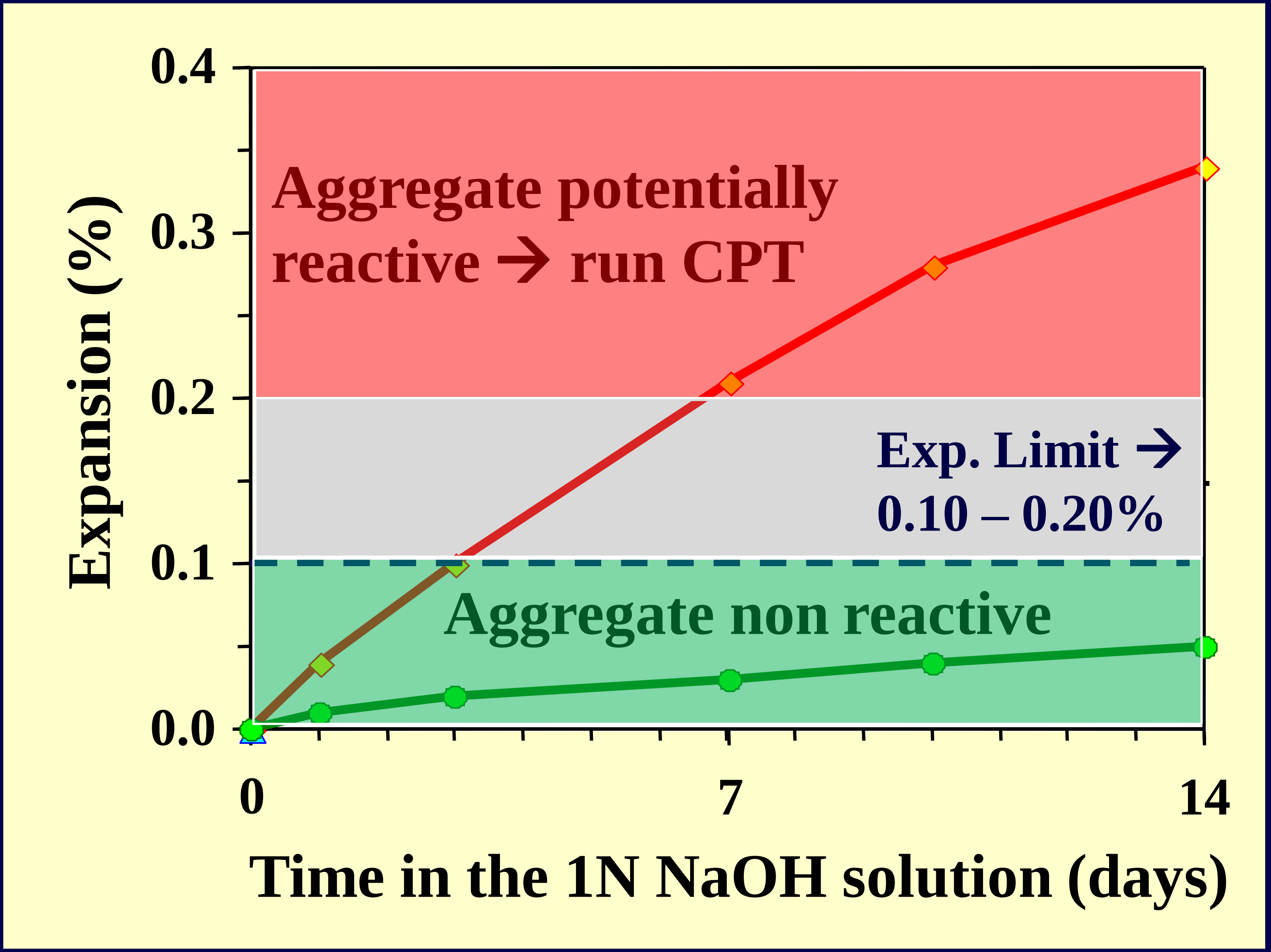
Accelerated Mortar Bar Test → ASR

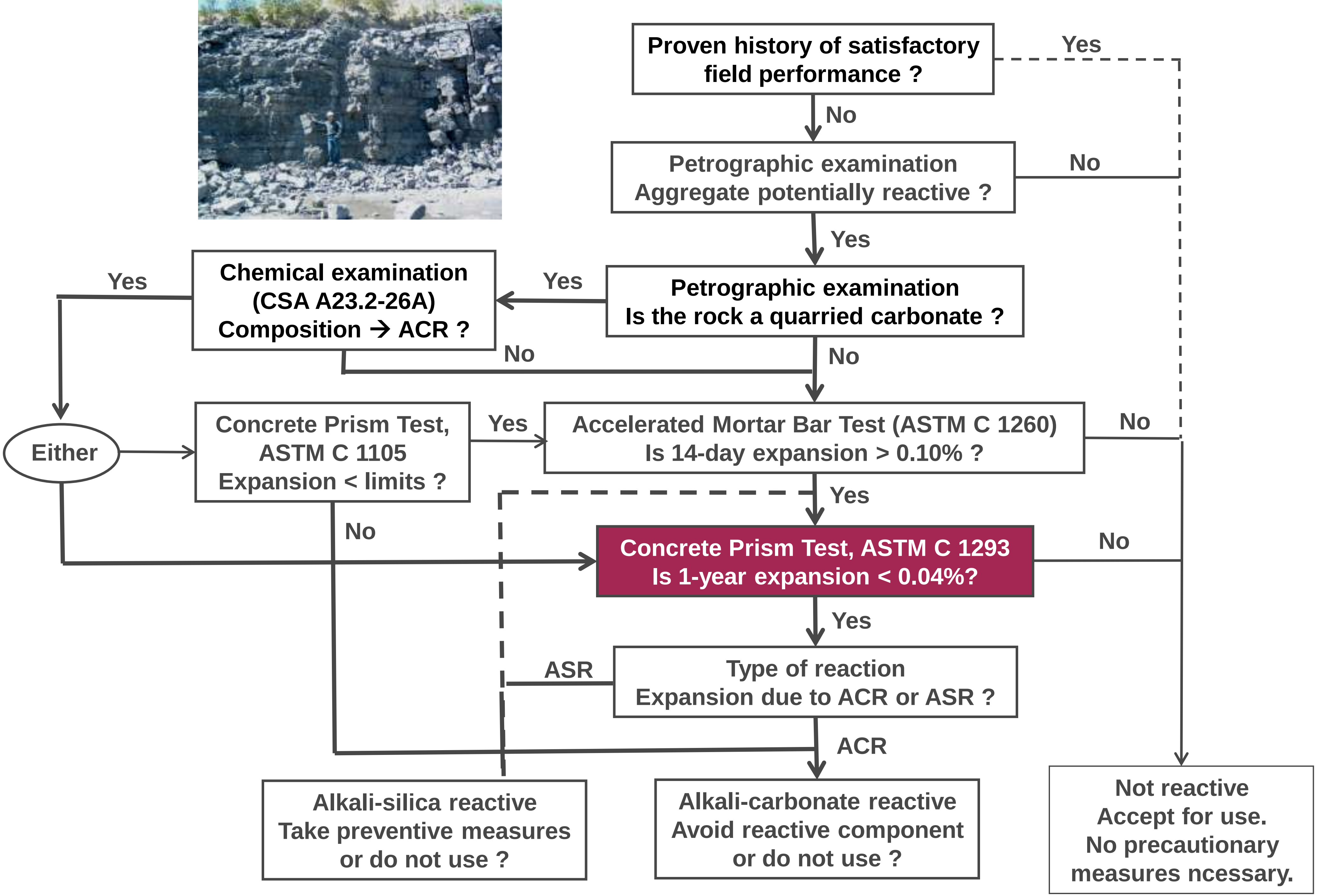
- **Mortar bars, 25 x 25 x 285 mm in size**
- **Particle size: 0.15 – 4.75mm**

Accelerated Mortar Bar Test → ASR

- Immersed 1N NaOH @ 80°C for 14 days
- Severe test conditions; ~ good screening test
  - Not to be used for rejecting aggregates

Accelerated Mortar Bar Test (AMBT)

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Not reactive
Accept for use.
No precautionary
measures ncessary.

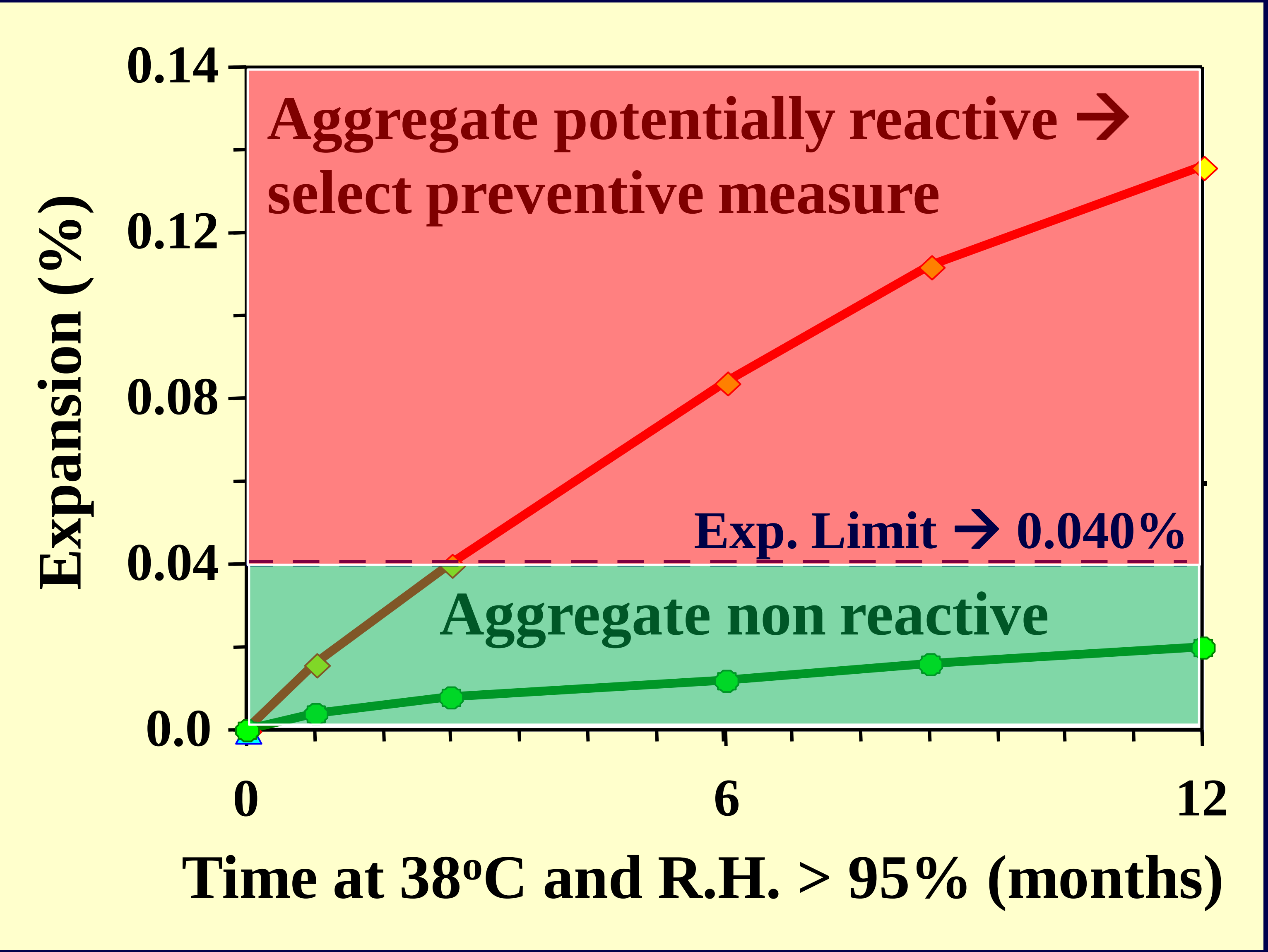
Concrete Prism Test → ASR & ACR

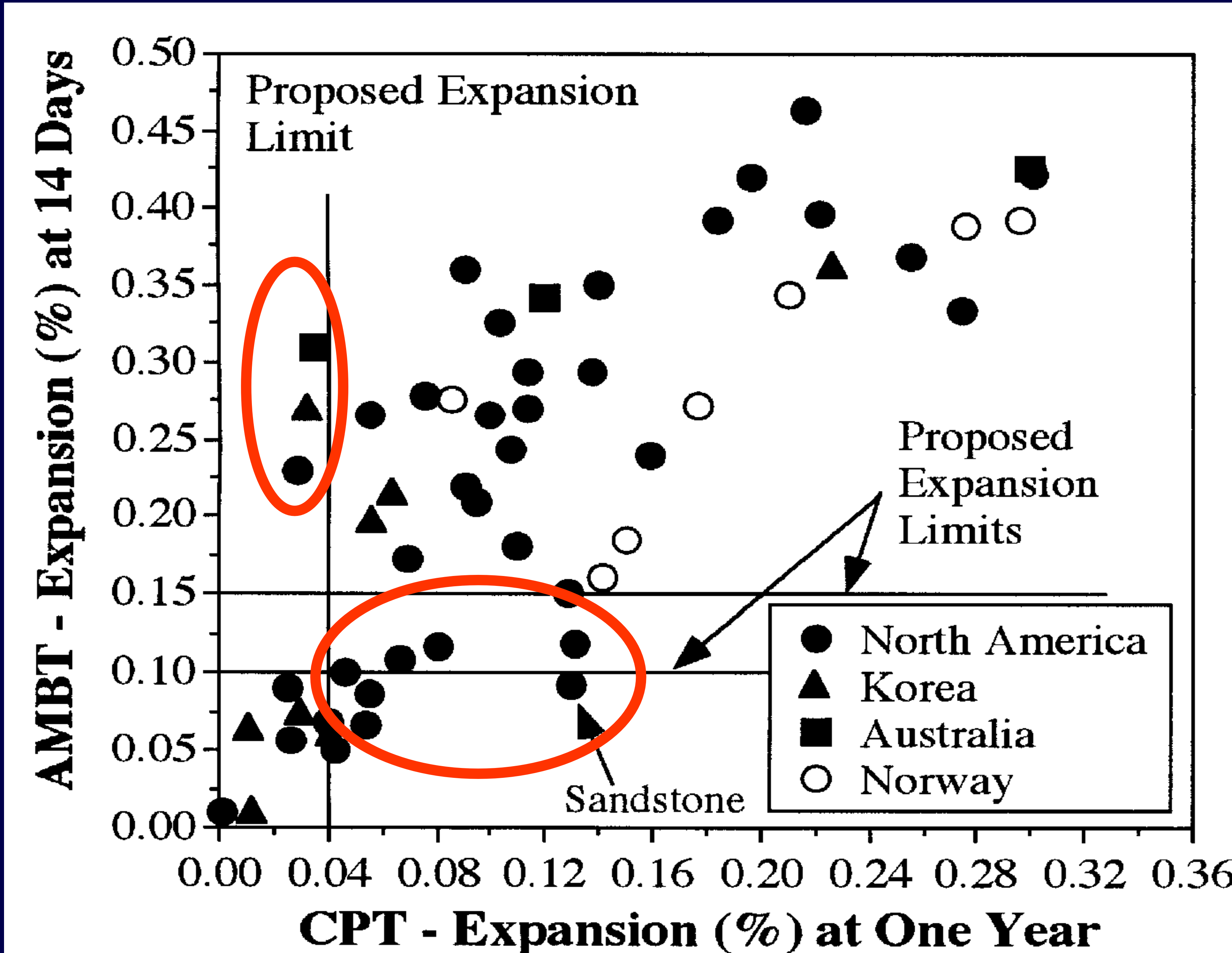
- Concrete prisms, 75 x 75 x 300-400 mm in size
- Cement content of 420 kg/m^3
- Particle size:
  -20 + 5 mm
- Alkalis boosted to
  1.25% Na_2Oeq,
  by cement mass

Concrete Prism Test → ASR & ACR

- **Prisms stored at 38°C and R.H. > 95%**

Concrete Prism Test (CPT)





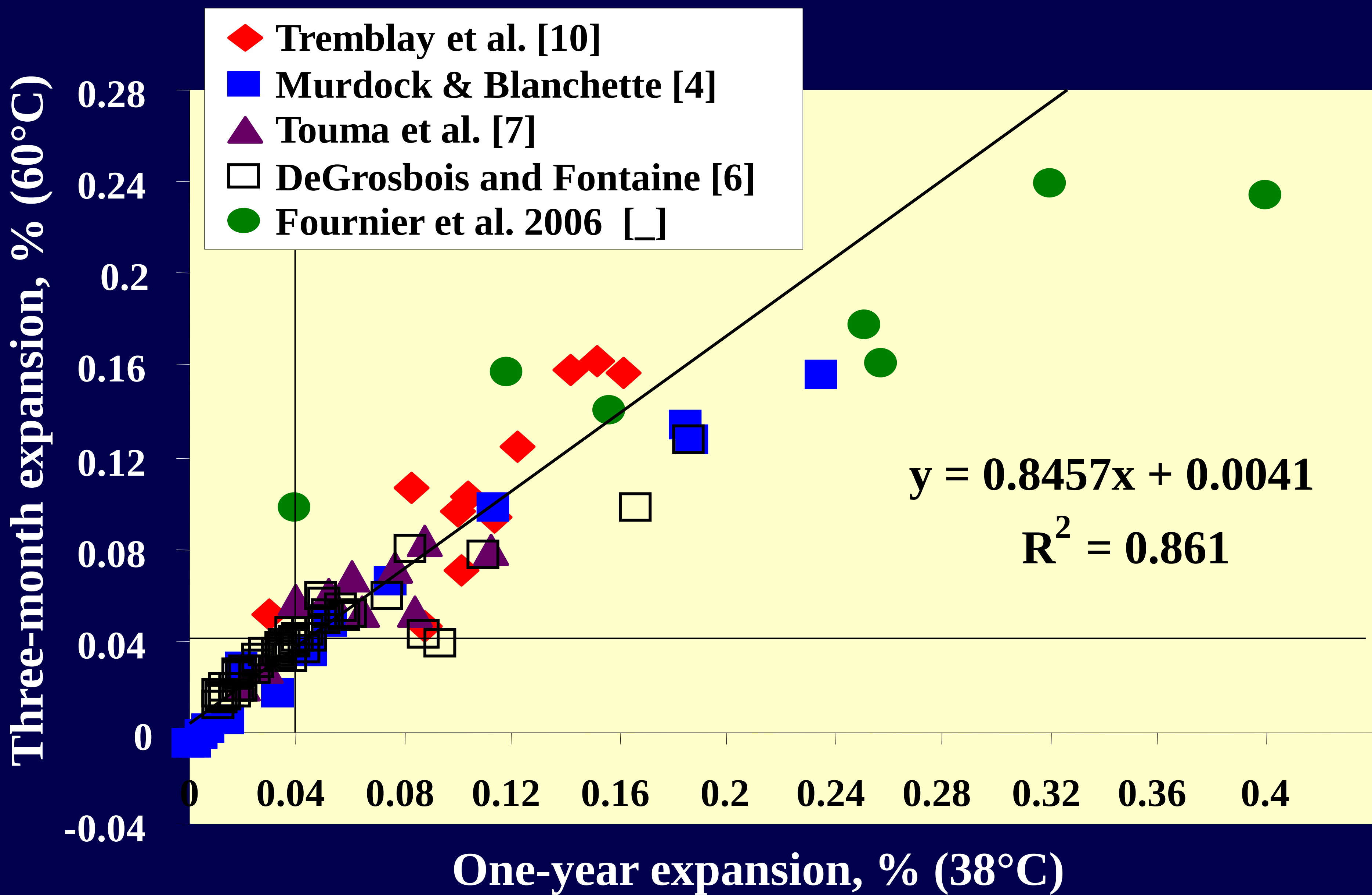
Proposed Expansion Limit
Proposed Expansion Limits
Sandstone
North America
Korea
Australia
Norway
AMBT - Expansion (%) at 14 Days
CPT - Expansion (%) at One Year
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.00 0.04 0.08 0.12 0.16 0.20 0.24 0.28 0.32 0.36

Storage Conditions (60ºC) – “Reactor”

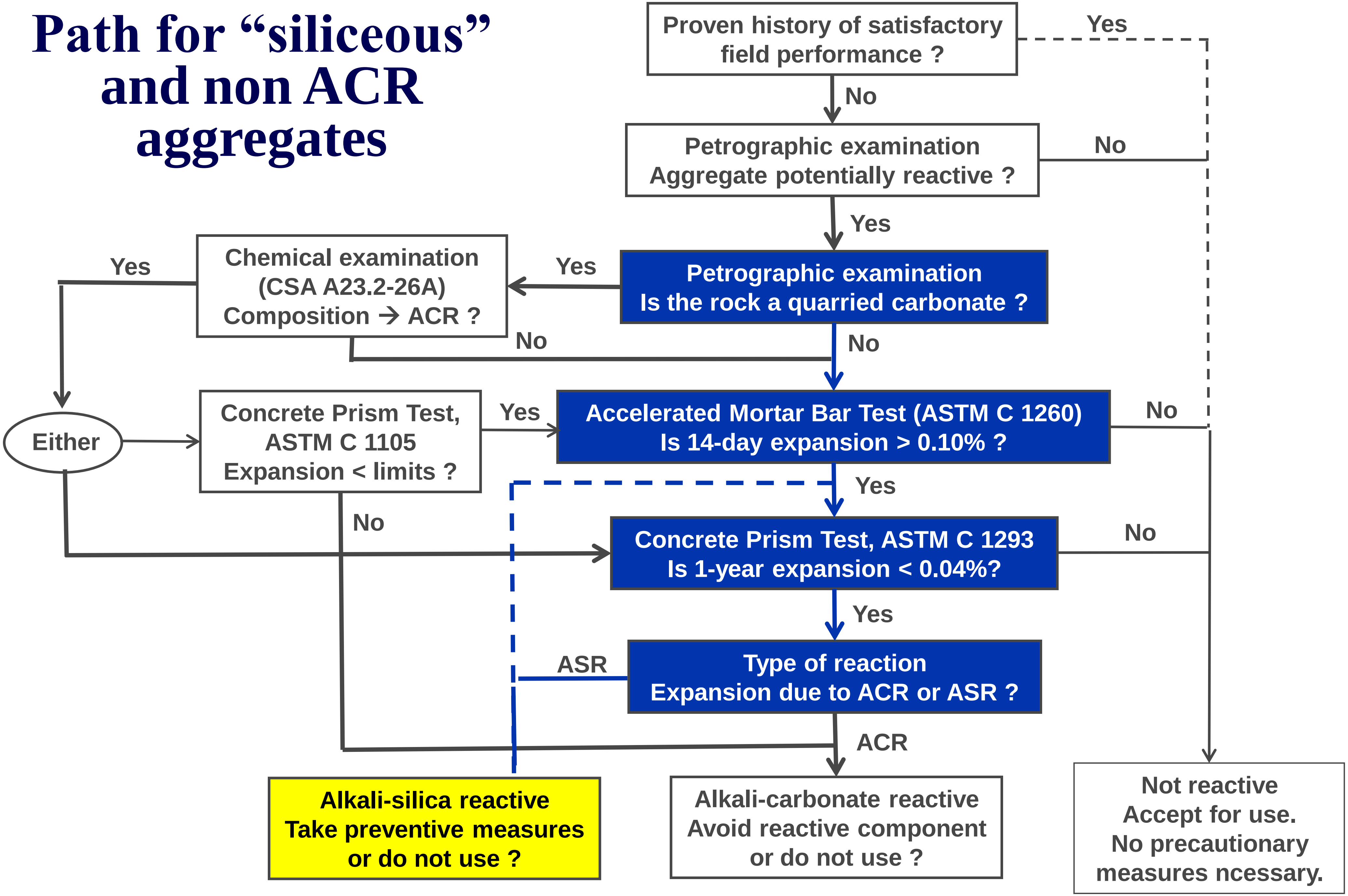
“Reactor” and Steel boxes

“Reactor” and Plastic pails

ACPT (60ºC) vs Conventional (38ºC) CPT

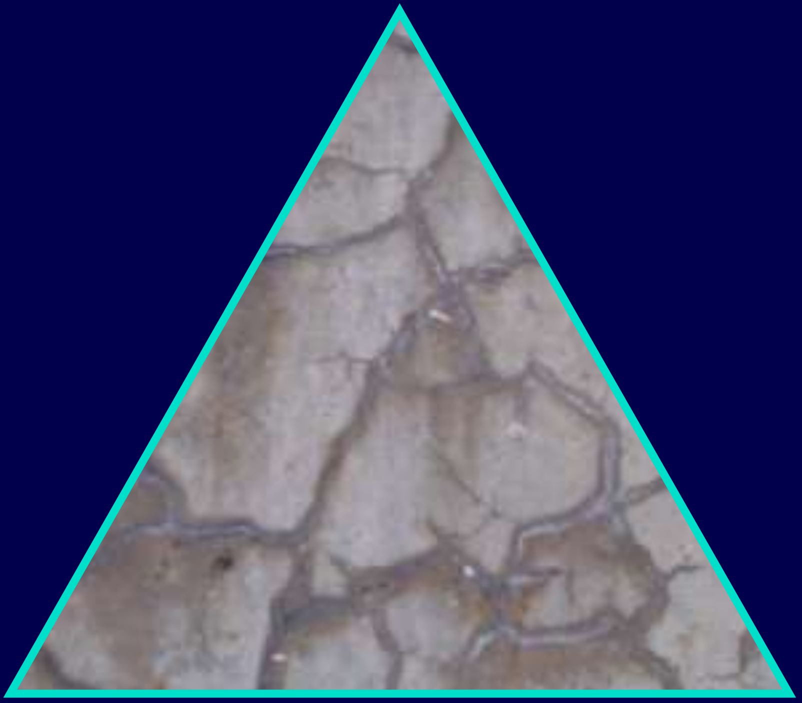


Path for "siliceous" and non ACR aggregates



Preventive Measures Against ASR

Reactive Material
in the aggregates

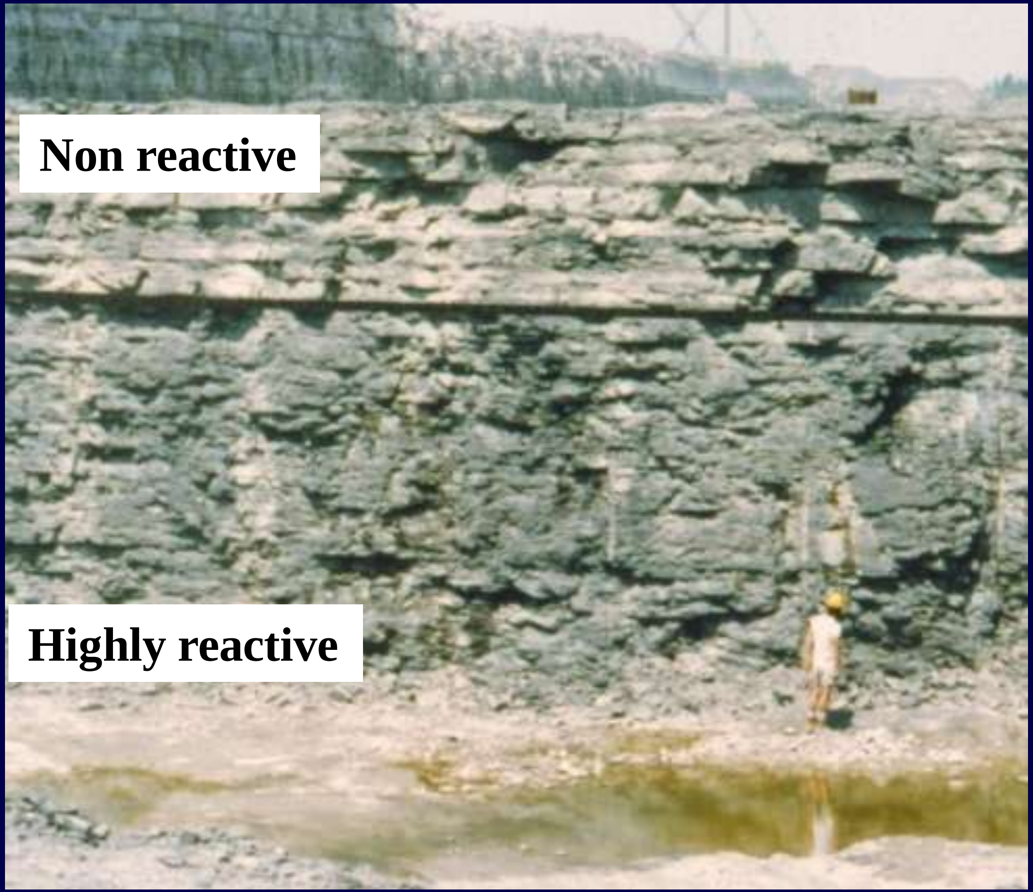


Sufficient
Alkali

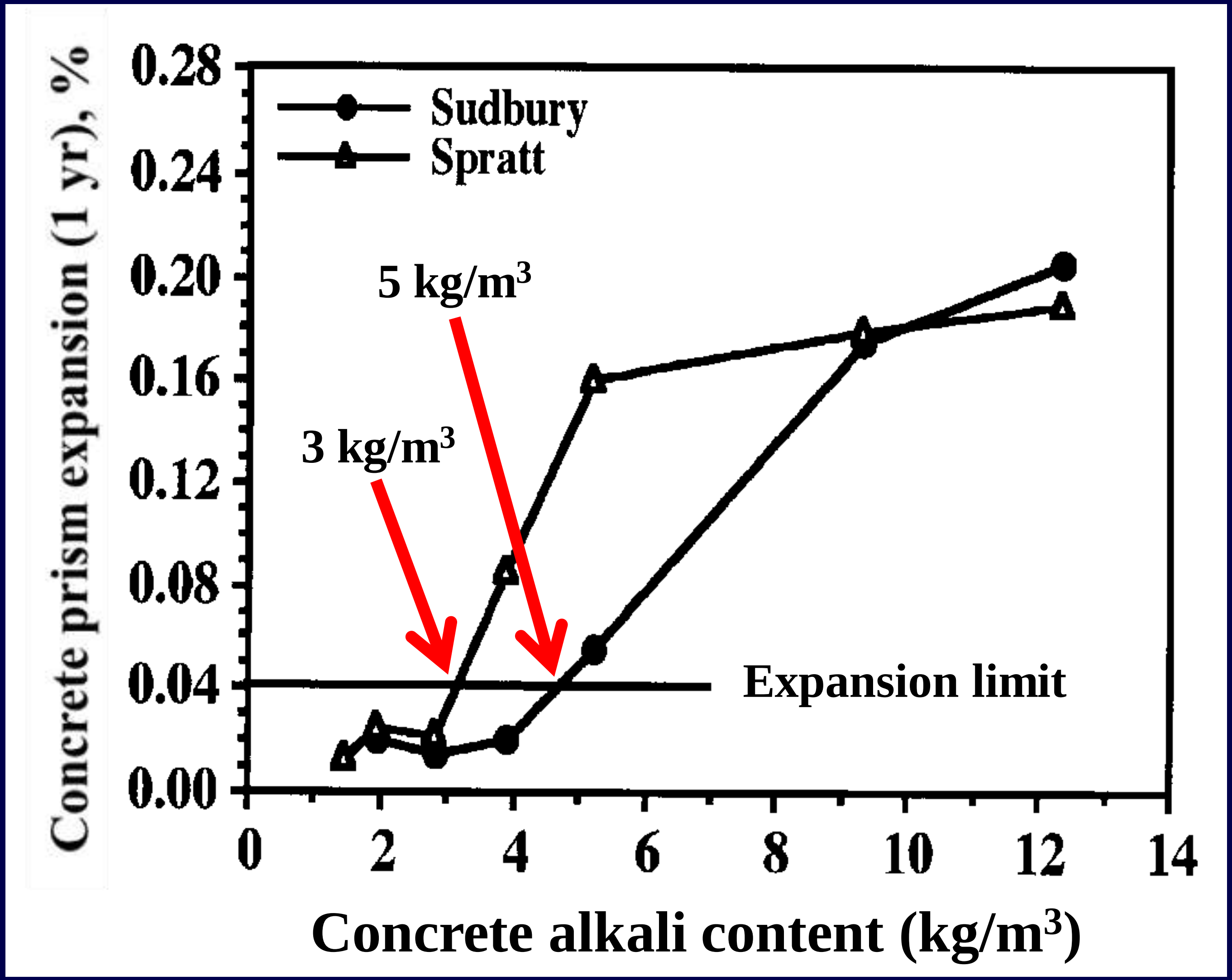
Sufficient
Moisture

Preventive Measures Against ASR

- Use non-reactive aggregate
  - Not always possible; not available; transport NR aggregates over long distances → $$$, GHG emissions !
  - Selective quarrying
  - Aggregate beneficiation



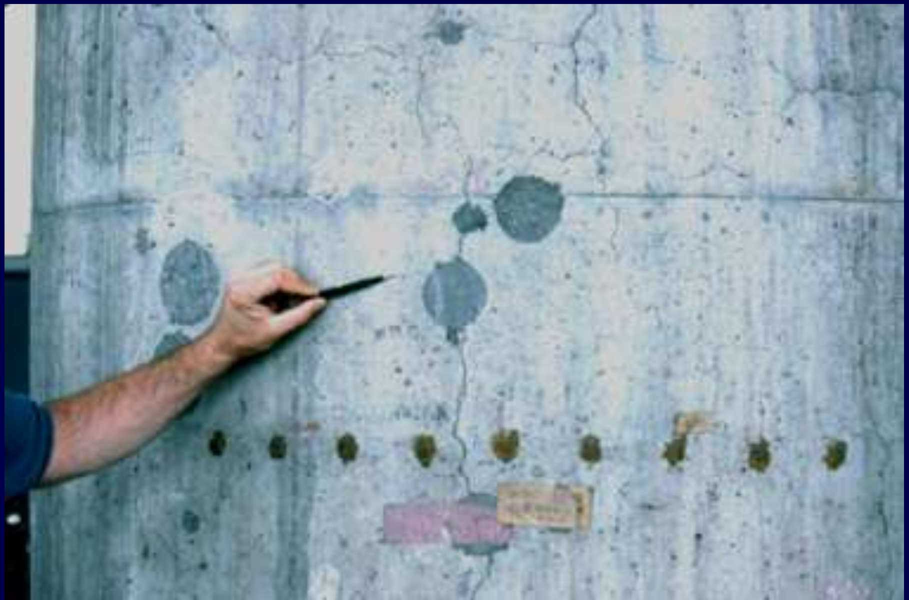
Limiting the alkali content in concrete



Preventive Measures

- Control the alkali content of the concrete mixture ???

Internal contribution from aggregates !!



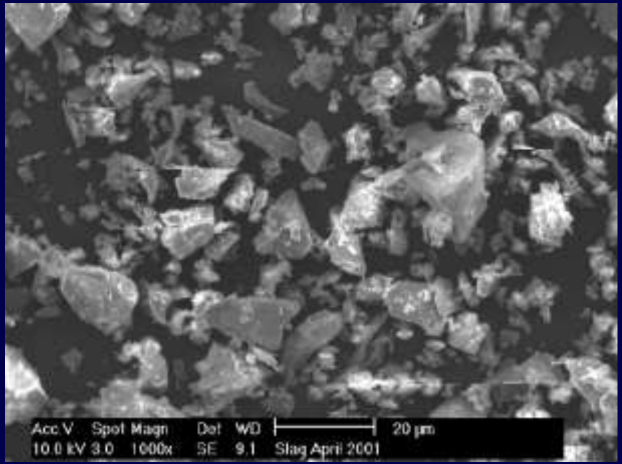
Internal contribution from sea-dredged sand

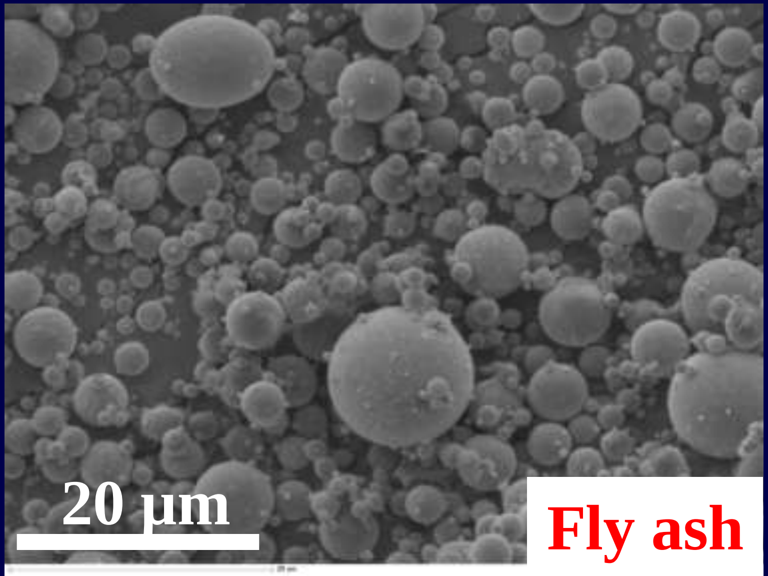
Supplementary cementing materials

Preventive Measures Against ASR

- Use a sufficient amount of efficient SCM(s)

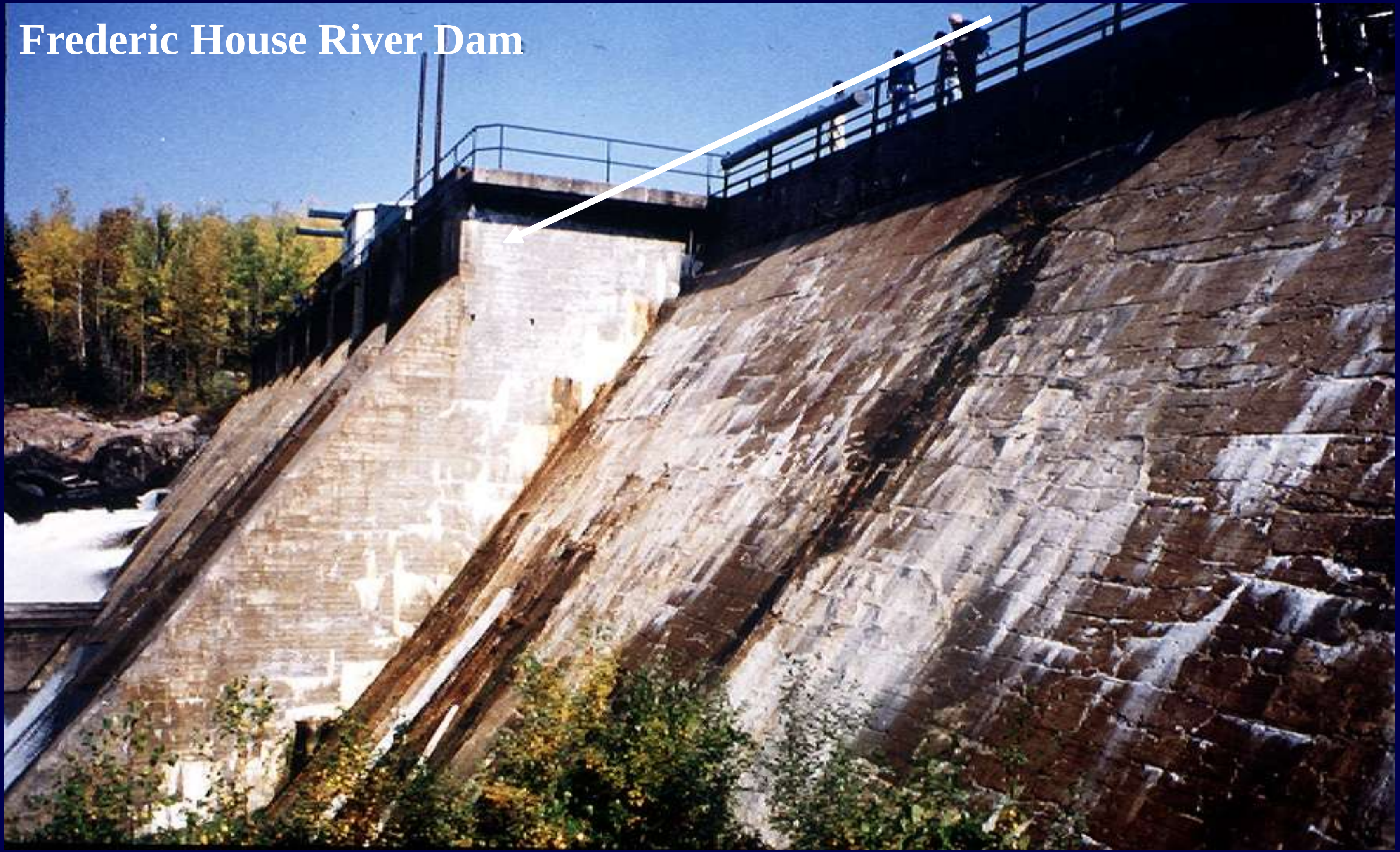
GGBFS





Field Performance of FA Concrete

- Hydraulic dams (Northern Ontario, Canada)



Conventional concrete → no SCMs

Field Performance of FA Concrete

- Hydraulic dams (Northern Ontario, Canada)

High-alkali cement + 30% Class F FA

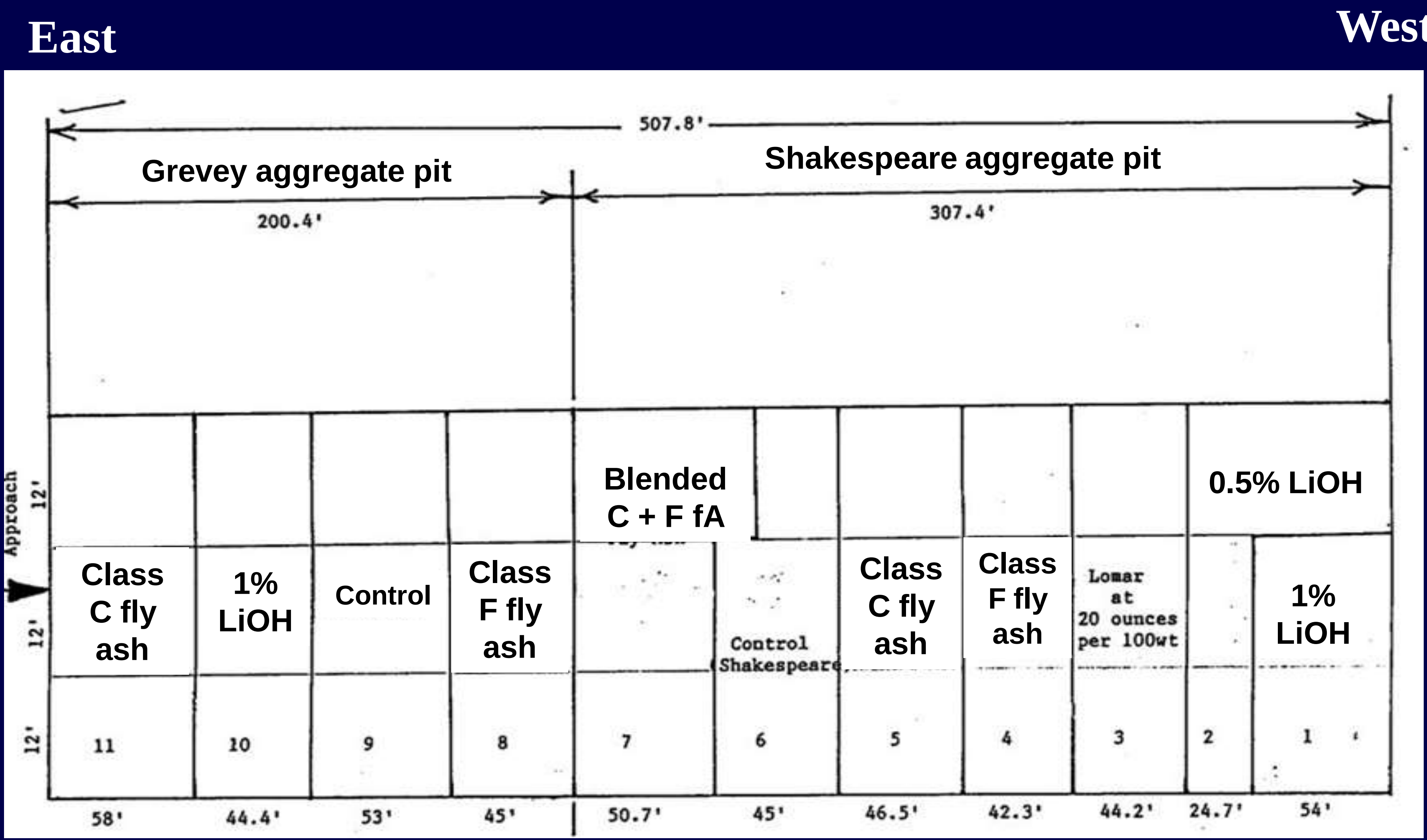
Field Performance of FA Concrete

- Lower Notch dam (Northern Ontario, Canada)

Pavement sections (New Mexico, USA) (1992)

Source : www.google.maps.com

Pavement sections (New Mexico, USA)

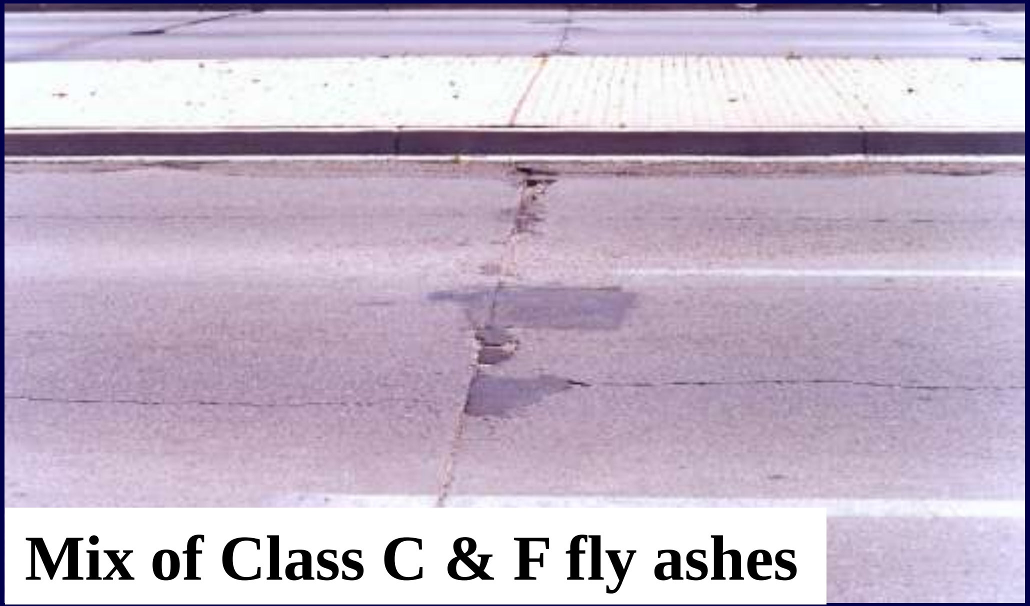


Source : USDOT, 2006

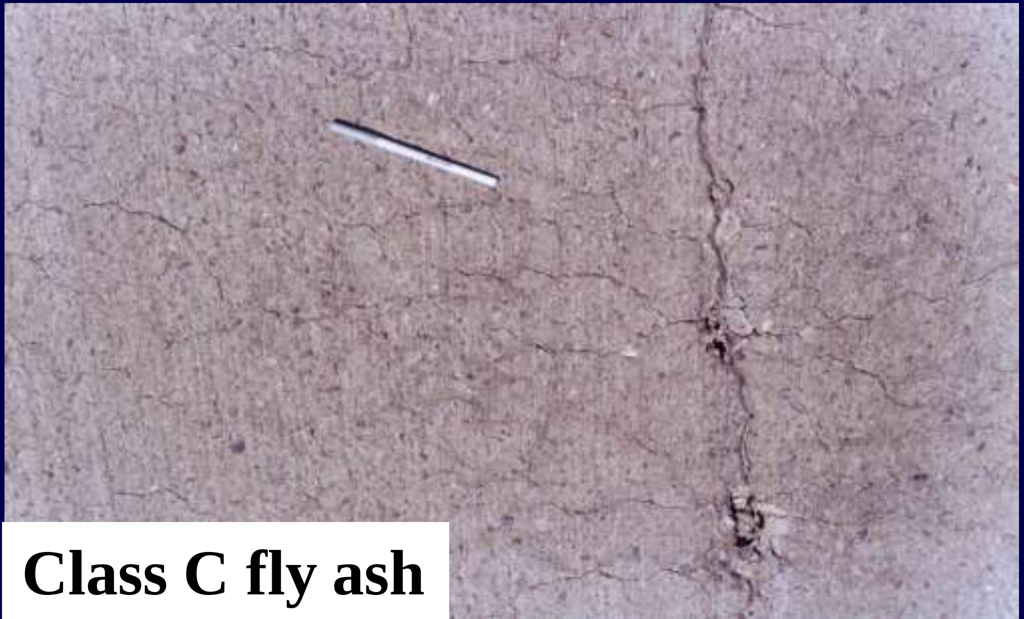
Field performance of fly ash concrete

- **Pavement sections (New Mexico, USA) (15 years)**

Testing site



Mix of Class C & F fly ashes



Class C fly ash

Field performance of fly ash concrete

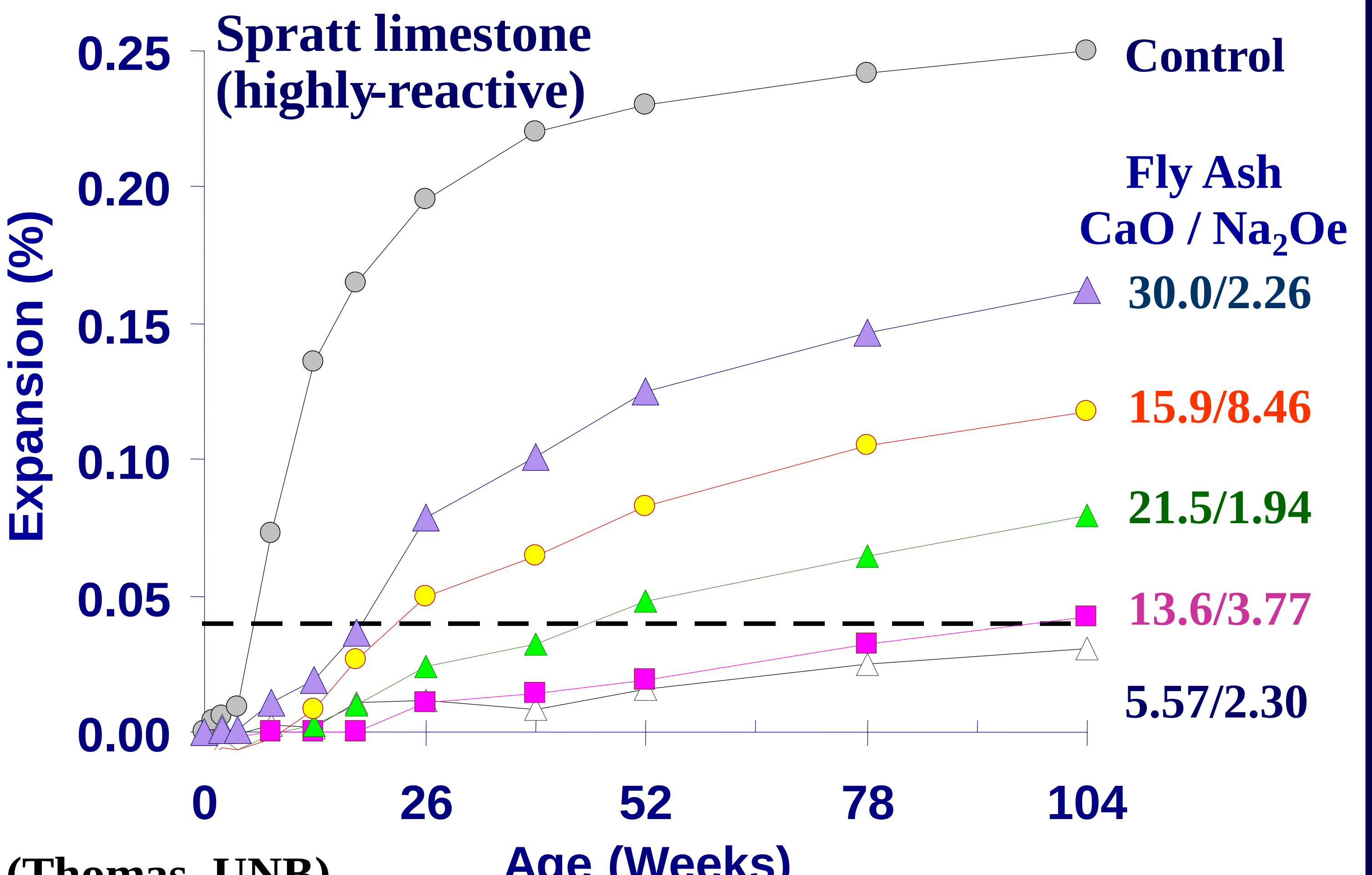
- **Pavement sections (New Mexico, USA) (15 years)**

Testing site

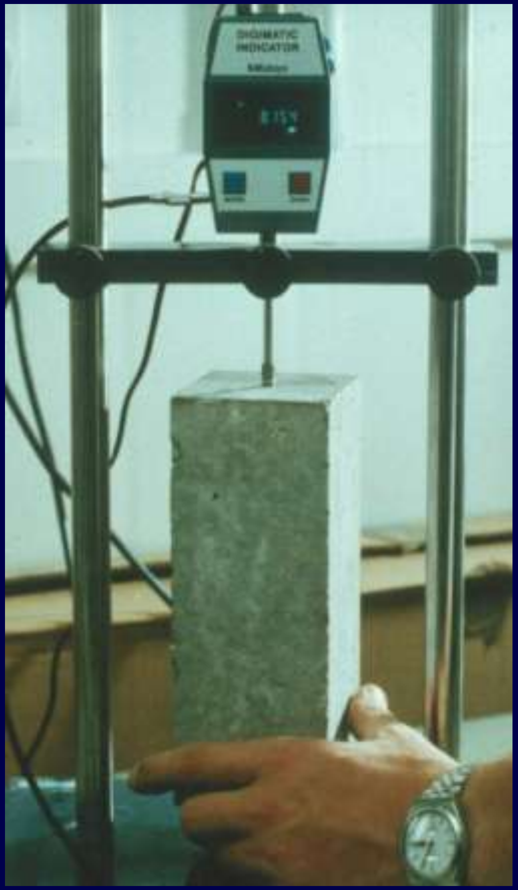
Class F fly ash

Effect of FA Composition on ASR Expansion

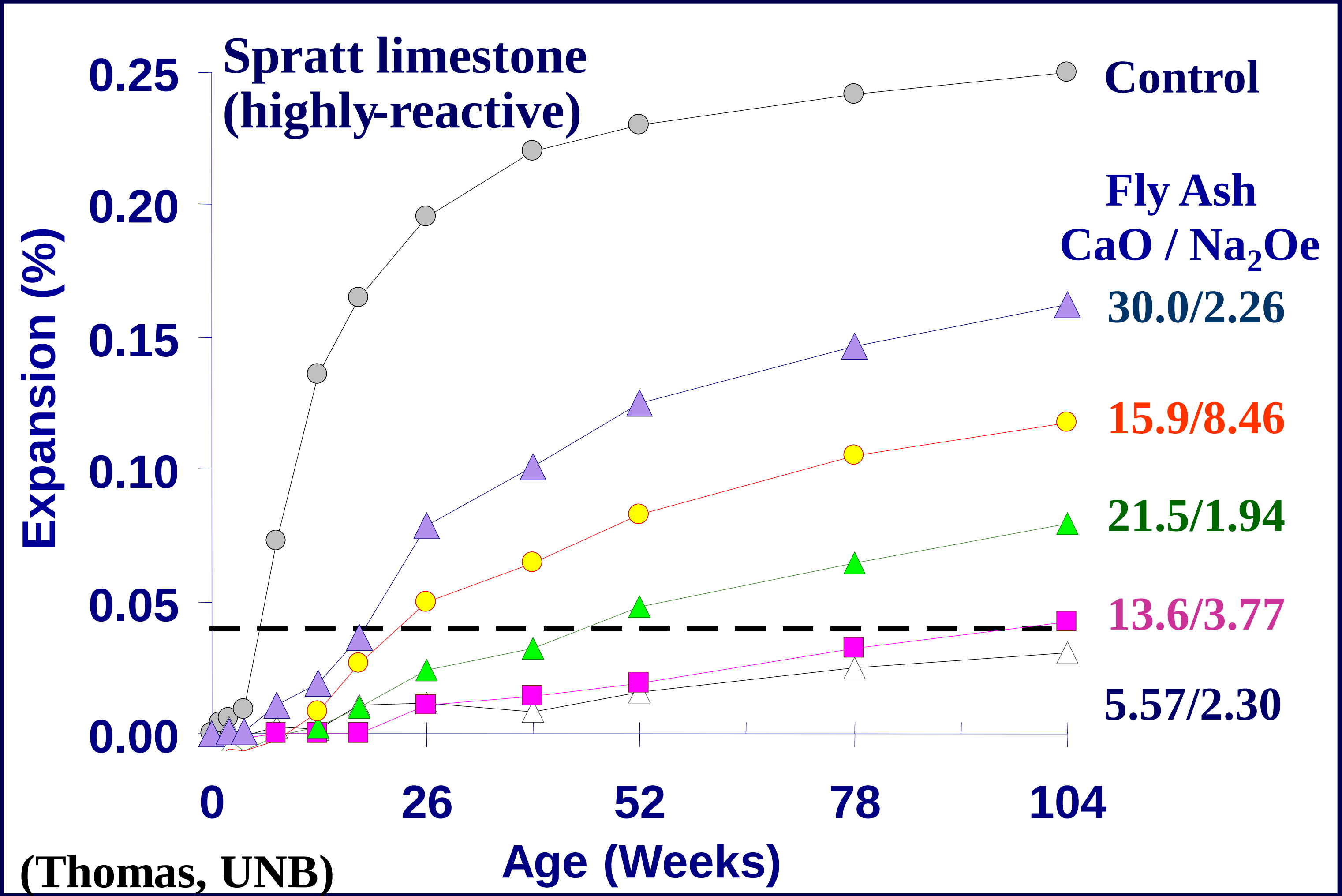
- Mixtures with 25% fly ashes



(Thomas, UNB)

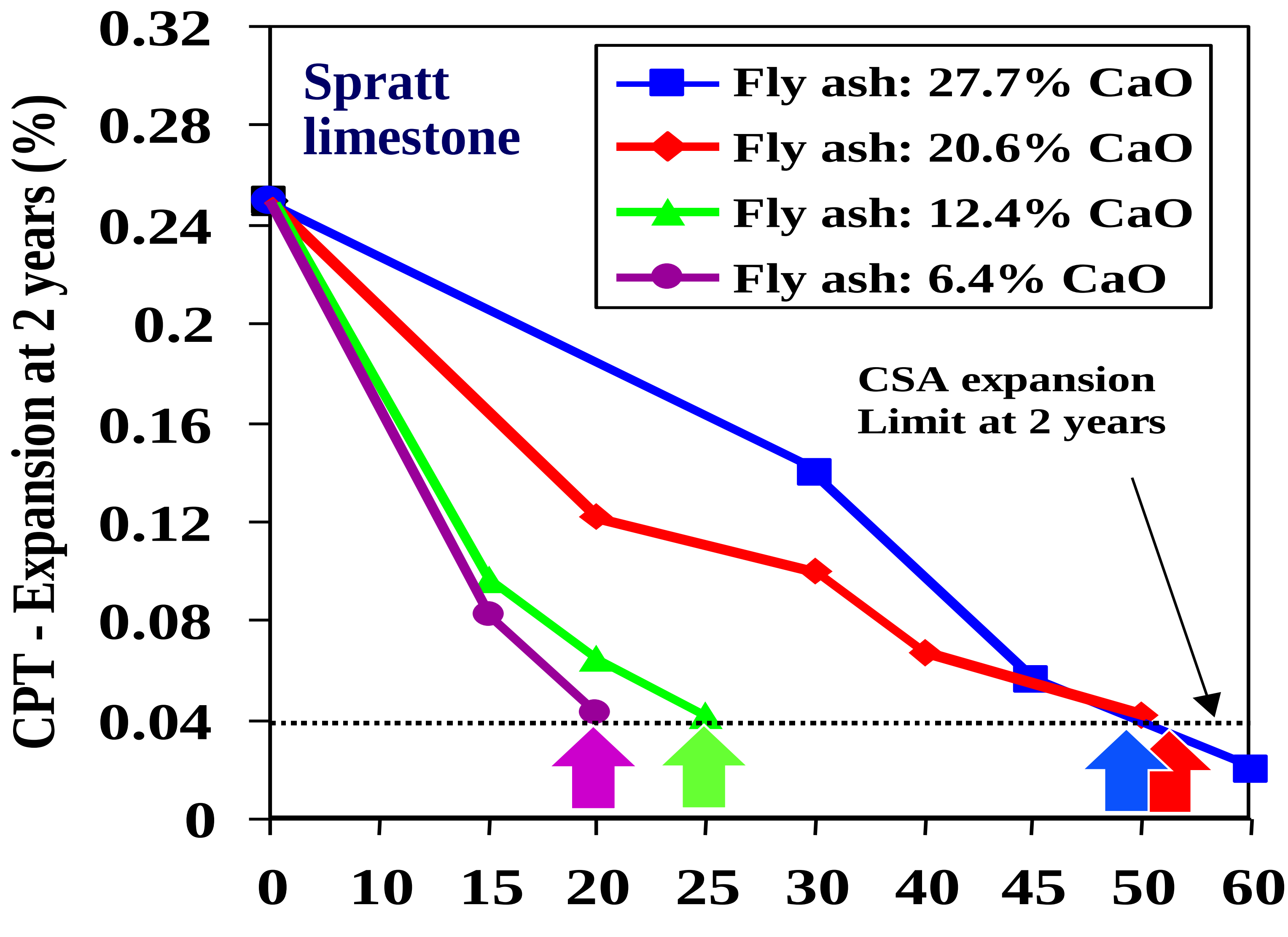


Effect of FA Composition on ASR Expansion



Efficacy against ASR ↓ with ↑ %CaO and %Na_2Oe

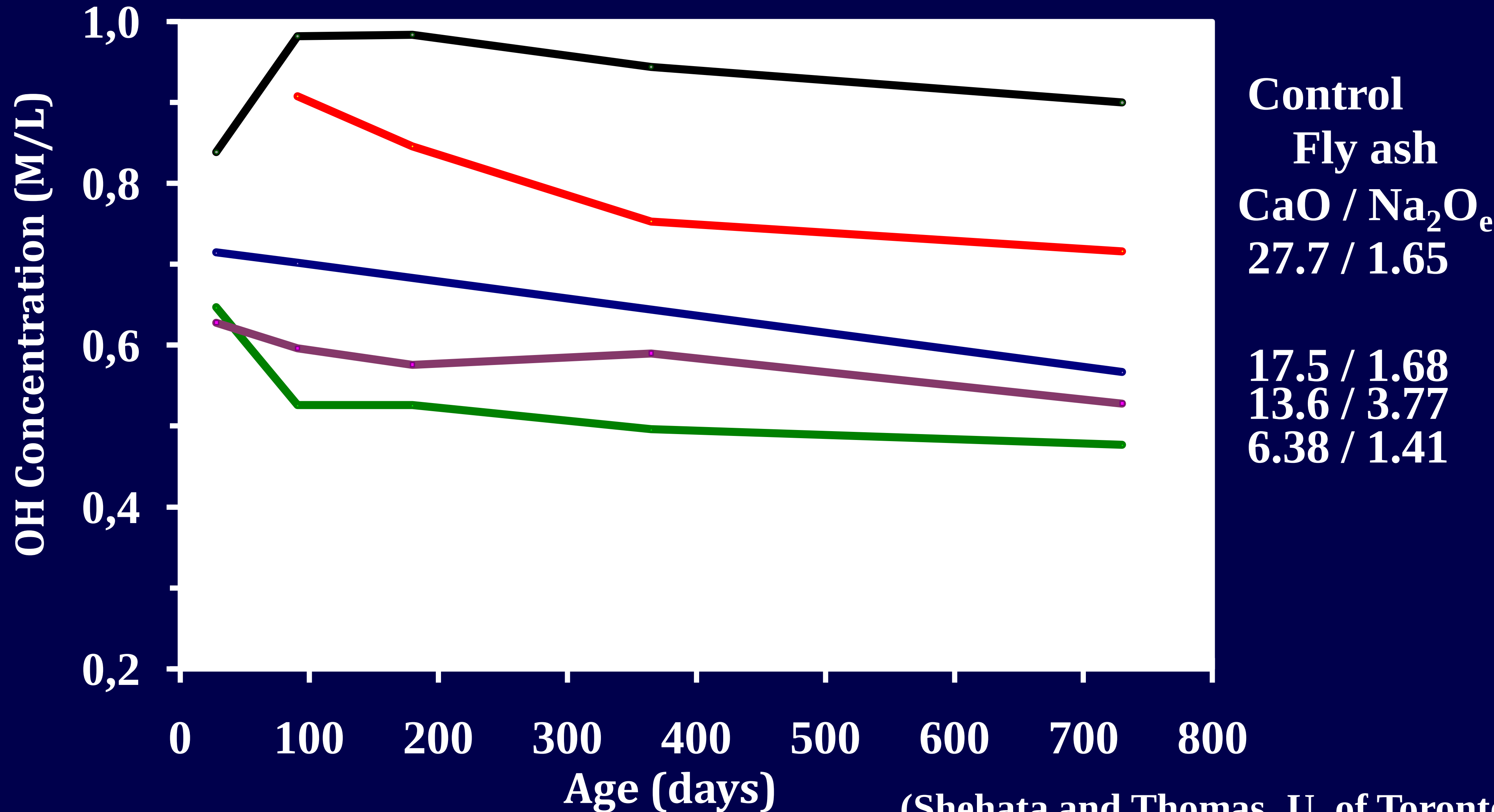
Effect of FA Composition & Proportion on ASR Expansion



(Thomas et al. 1999)

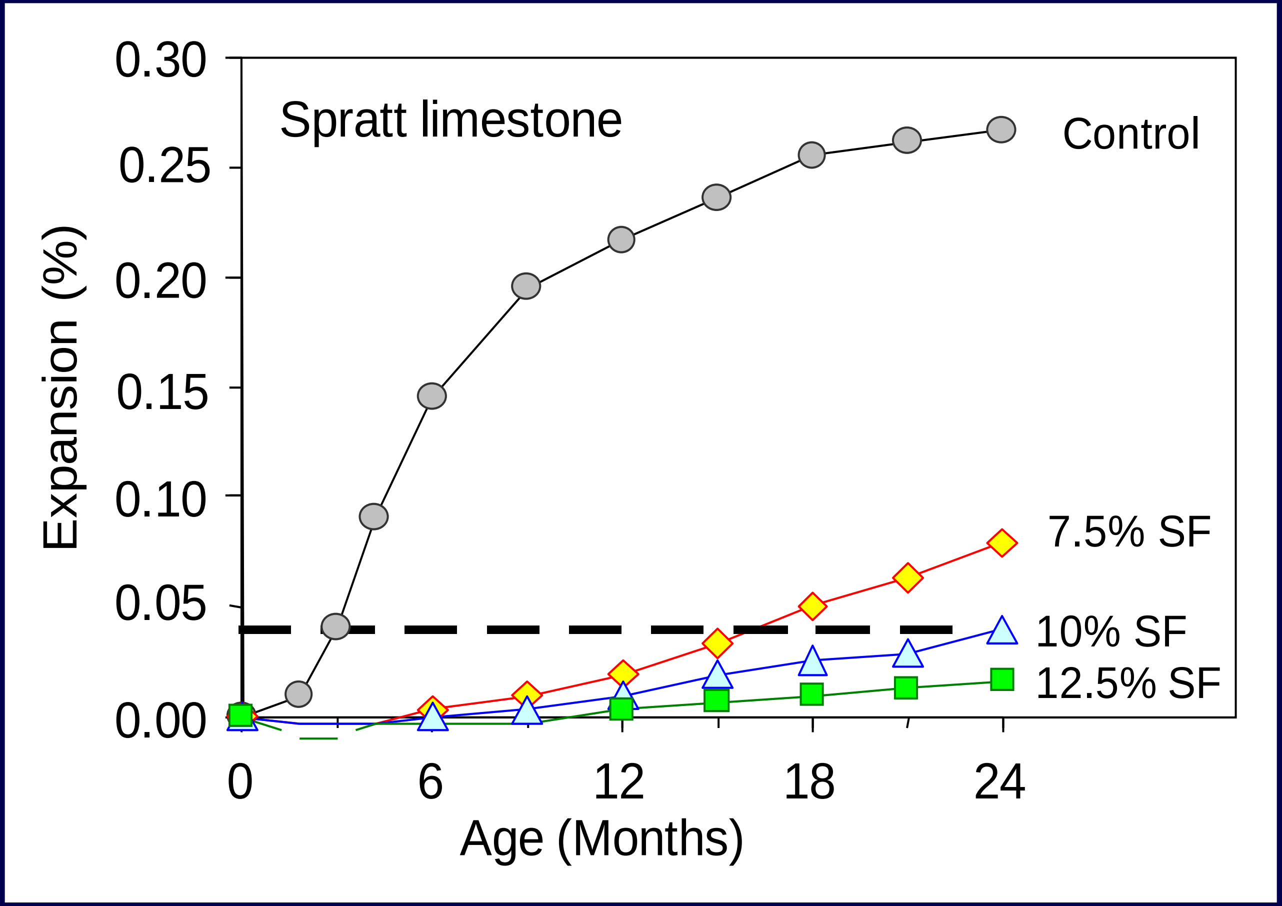
Effec of fly ash composition on the chemistry of the concrete pore solution

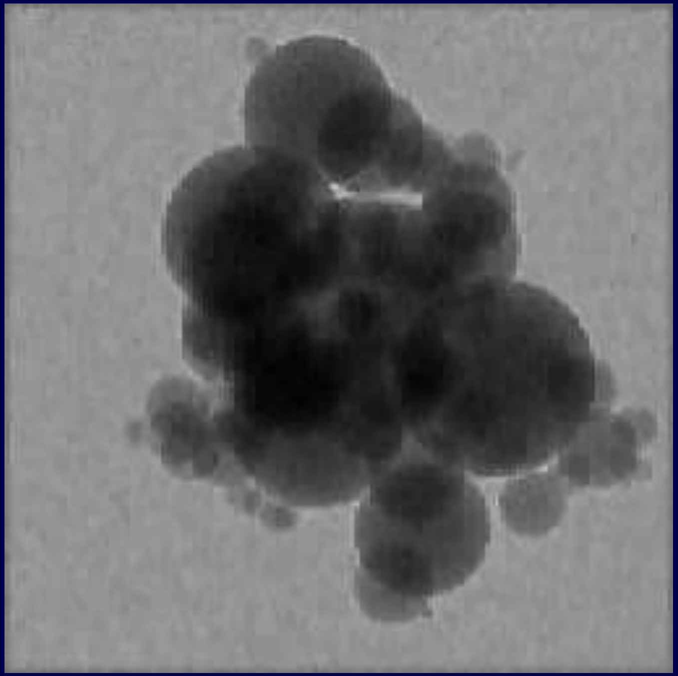
Cement paste with high-alkali cement & 25% FA



(Shehata and Thomas, U. of Toronto)

Silica Fume against ASR



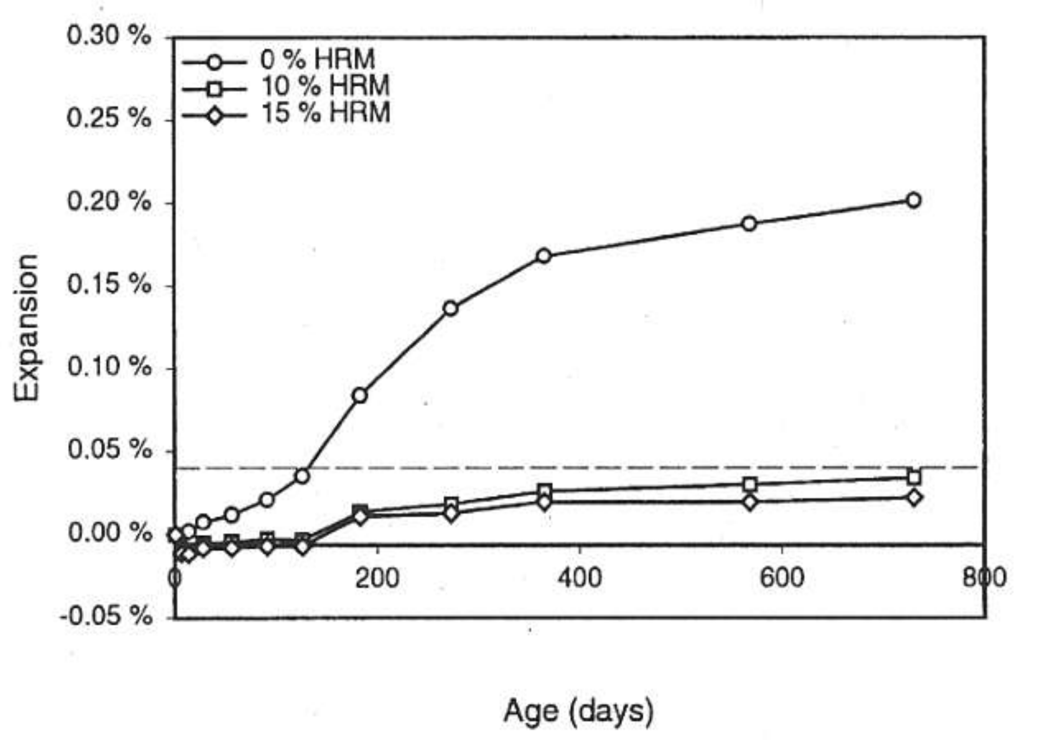


Particles 0.1 – 2 µm

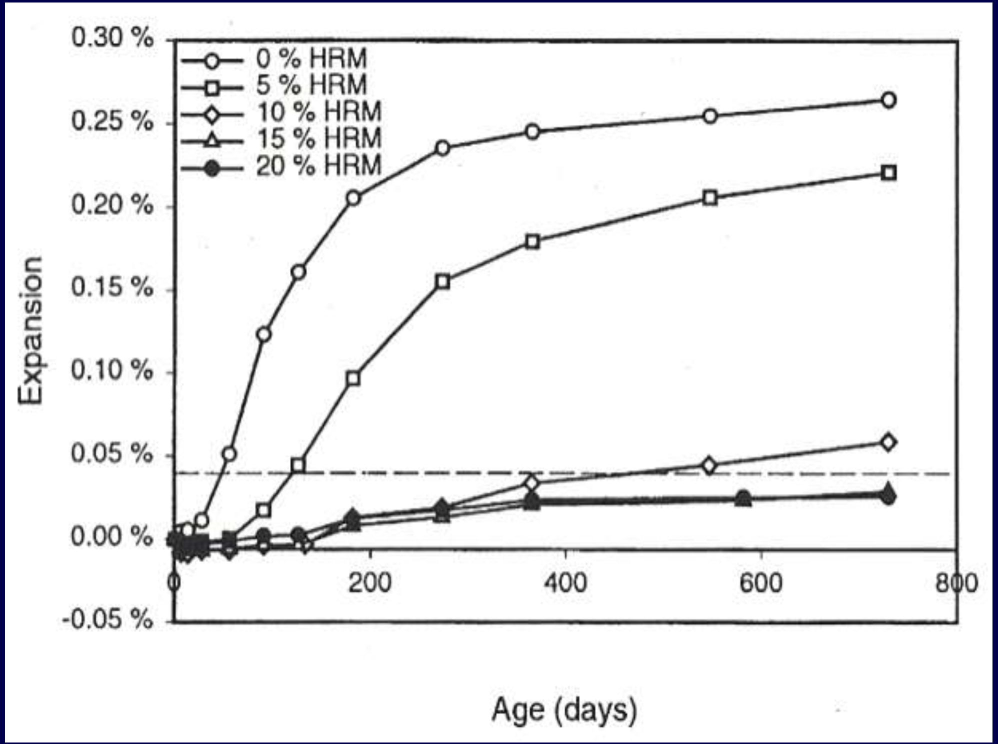
Fournier et al. 1995

Metakaolin against ASR

Moderately-reactive aggregate

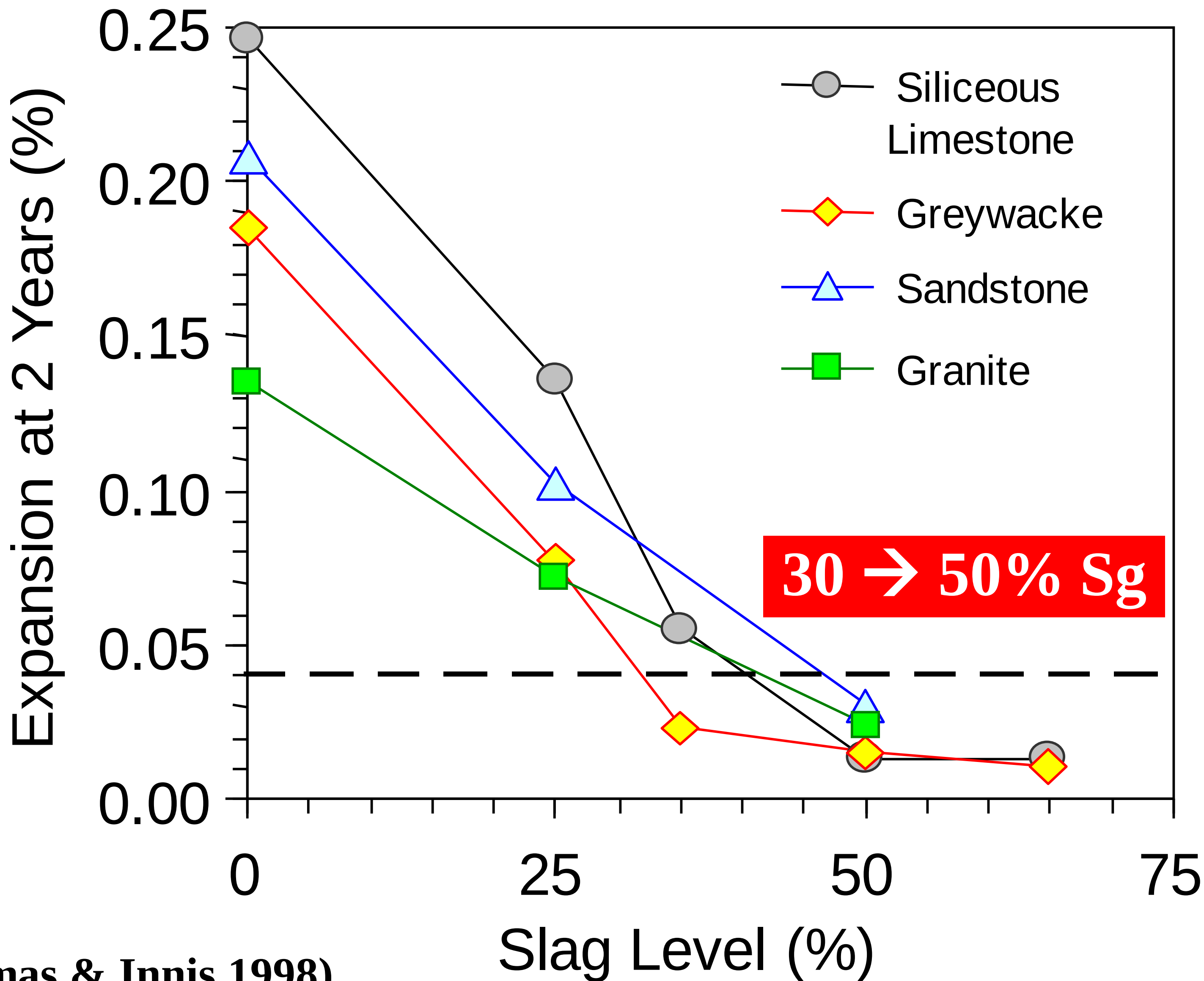


Highly-reactive aggregate



Ramlochan et al. 2000

Effect of Slag on ASR Expansion



(Thomas & Innis 1998)

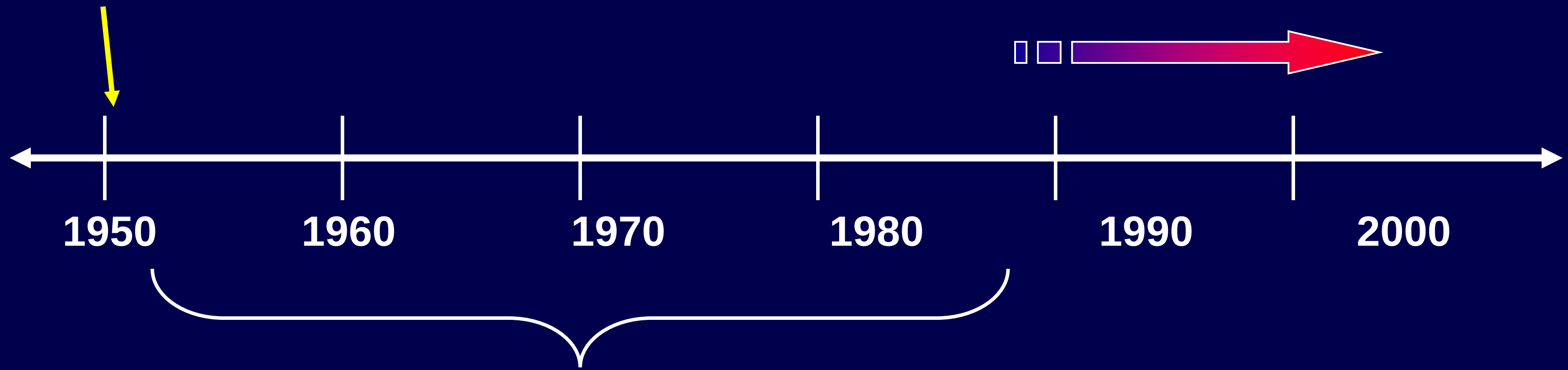
Preventive Measures Against ASR

- Use a sufficient amount of a chemical admixture (lithium-based product)

Lithium-based admixtures History and Background

McCoy and Caldwell (1951) → lithium compounds (LiF, Li_2CO_3, LiCl et $LiNO_3$) can suppress expansion due to ASR.

Renewed interest in lithium compounds, starting late 1980’s



Little research on using lithium to control ASR…

Adapted from Thomas & Folliard (2002)

Factors Influencing the Effectiveness of Lithium to Reduce ASR Expansion

- **Alkali loading and nature of the reactive aggregate**

- **The main factor is the <u>ratio lithium : alkali content of the concrete mixture</u>**

i.e. Molar ratio [Li] / [Na + K]

Alkalis in the concrete mixture

Factors Influencing the Effectiveness of Lithium to Reduce ASR Expansion

- **Alkali loading and nature of the reactive aggregate**
- **The main factor is the ratio lithium : alkali content of the concrete mixture**

i.e. Molar ratio [Li] / [Na + K]

Alkalis in the concrete mixture

Earlier research → [Li] / [Na + K] of 0.74 is OK with a large number of reactive aggregates → "Standard Dosage"

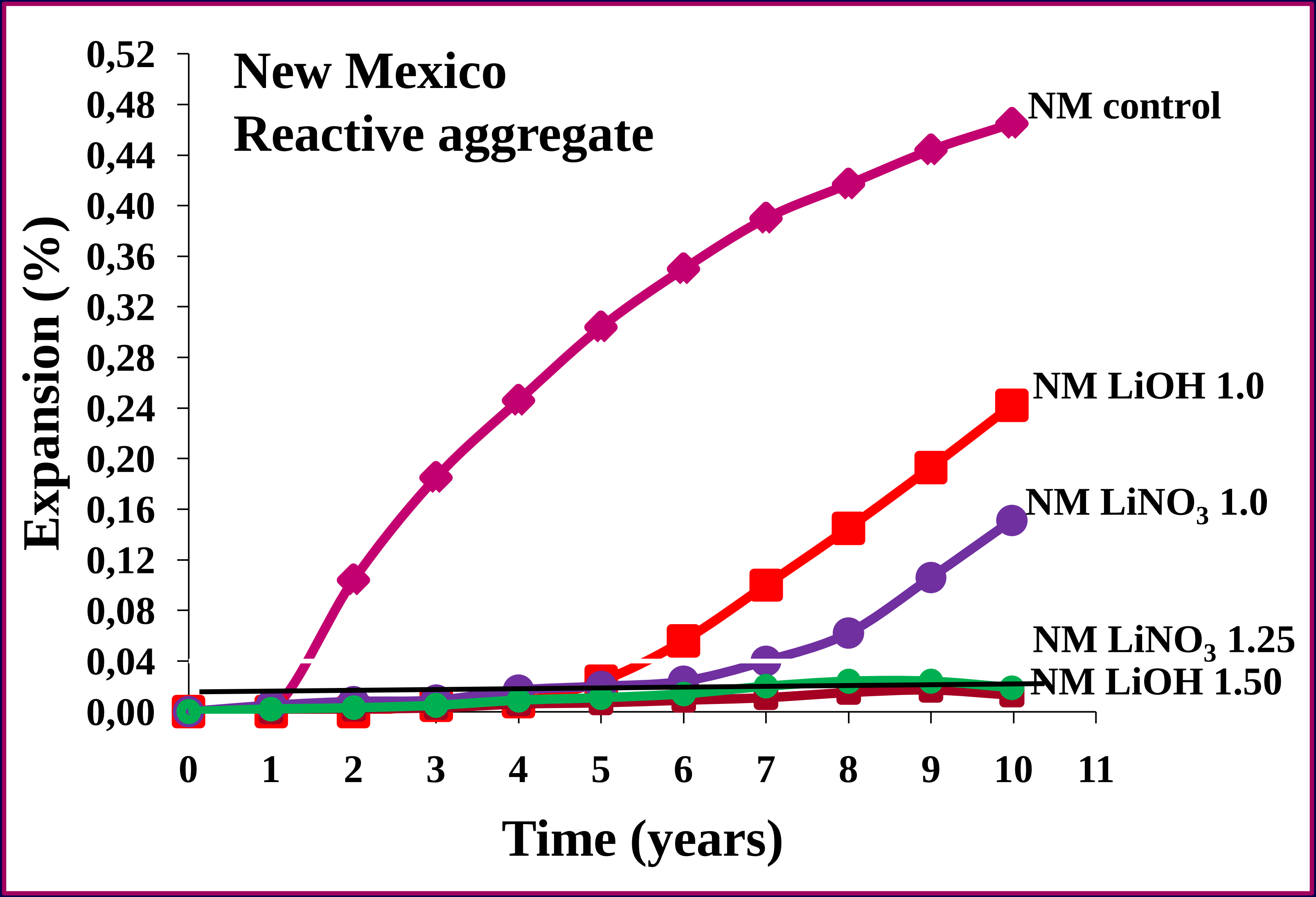
Lithium-based Admixtures

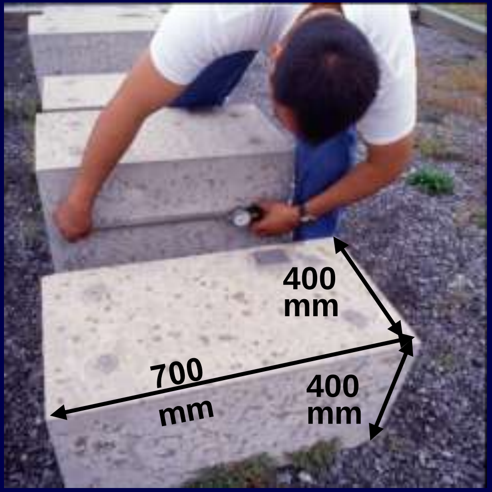
Standard Dosage → molar ratio of 0.74

- **1 kg of $LiOH \cdot H_2O$ / kg of Na_2Oeq in the concrete**

- **4.6 L of $LiNO_3$ solution / kg of Na_2Oeq in the concrete**

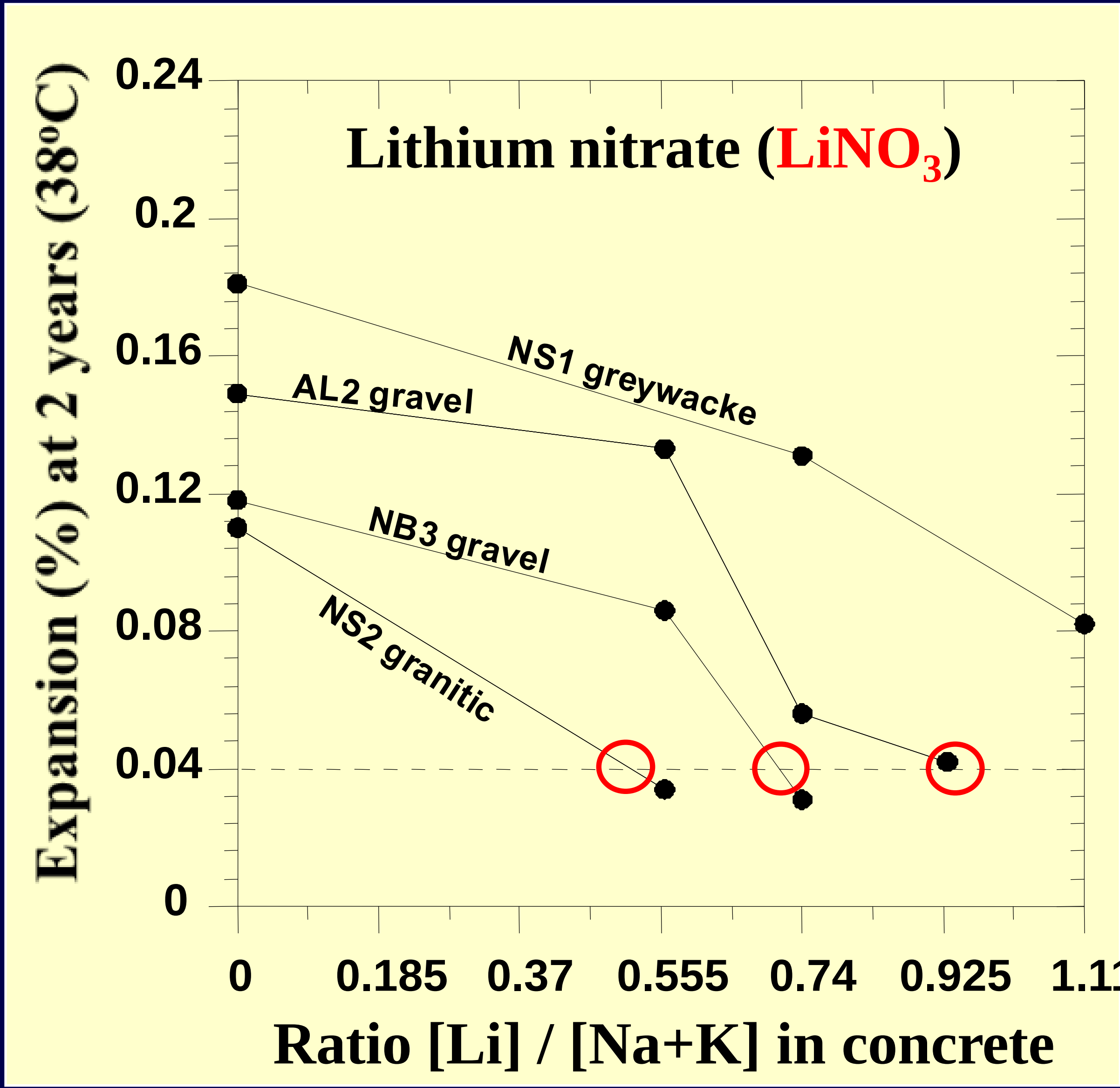
Use of Lithium to control ASR expansion
Exposure blocks





Preventive Measures Against ASR

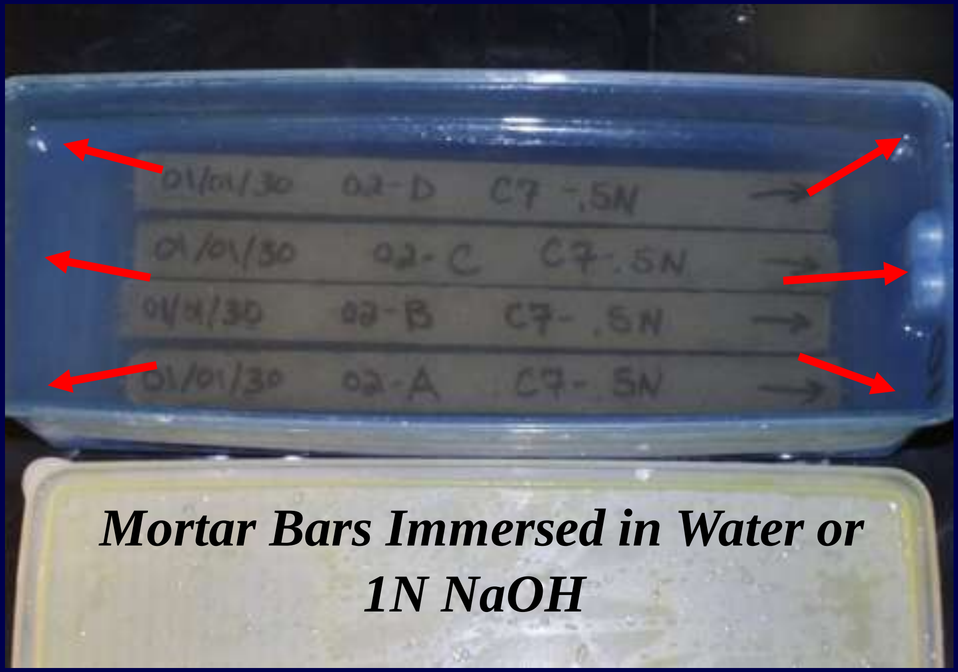
- Amount of lithium-based product needed varies depending on the reactive aggregate



(Tremblay et al. 2007)

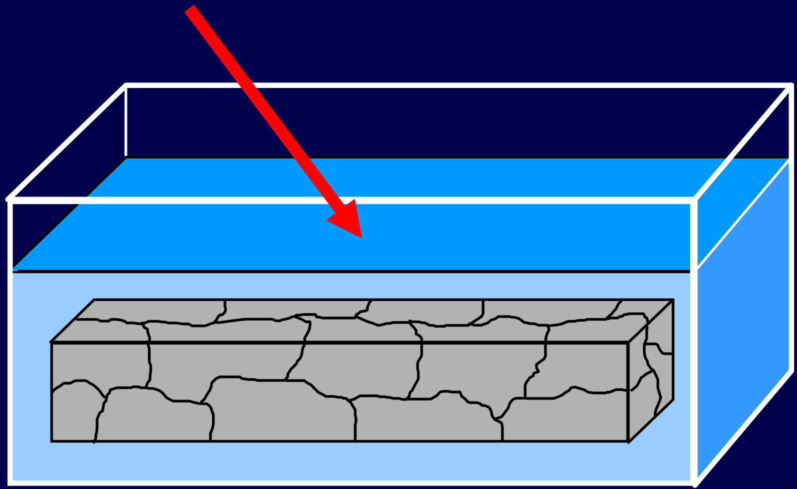
Accelerated testing for lithium dosage

- CPT is the preferred test → <u>2-year</u>, 0.04% exp limit)
- <u>Modified</u> version of AMBT
  - Lithium to be added in the bar and the soak solution
  - Expansion limit ~ 0.10% @ 28 days



Mortar Bars Immersed in Water or 1N NaOH

To control leaching, ASTM C 1260 is modified by adding Li to the soak solution



Modified AMBT – proposed approach

Begin by Testing the Aggregate with the following two mixtures :

1. **Control mixture (Expansion at 28 days = E1)**
2. **Mixture with lithium : [Li]/[Na+K] = 0.74 in bar and [Li]/[Na]=0.148 in soak solution (Expansion at 28 days = E2)**

Is the ((E2-E1)/E1) < 0.1

Yes

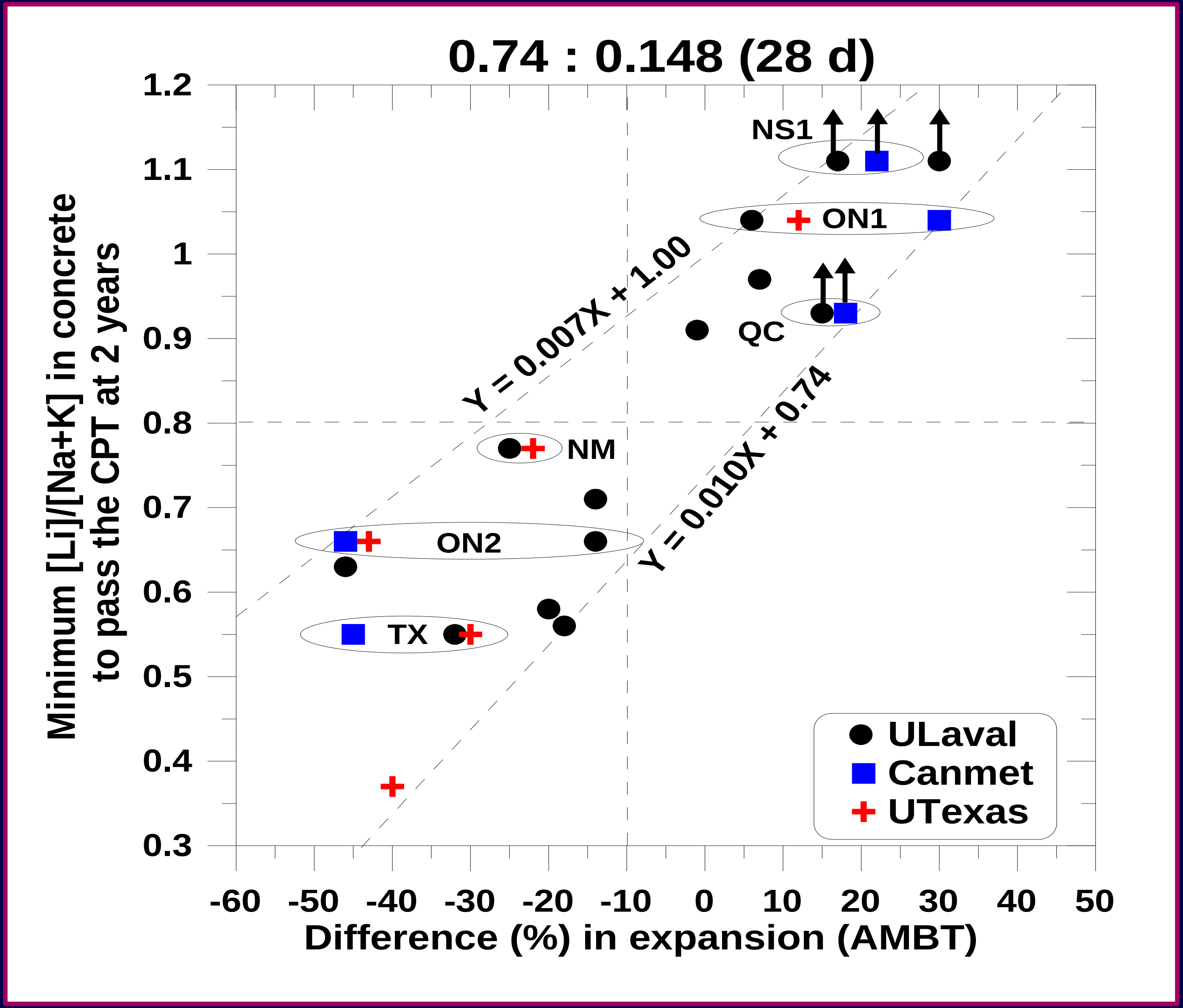
Use the following equation:
1.0 + 0.7 x ((E2-E1)/E1) = *Ratio*
The *Ratio* = [Li]/[Na+K] to use in concrete

No

Use concrete prisms test to evaluate the ratio to use

Tremblay et al. (2008)

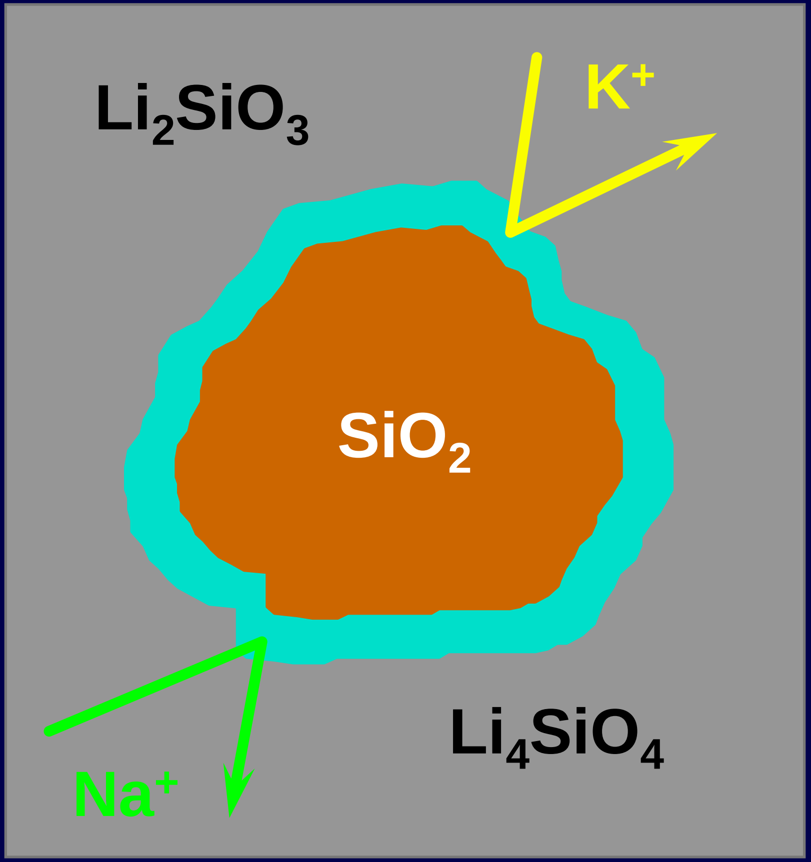
Modified AMBT – proposed approach



Tremblay et al. (2008)

How does lithium help?

- Formation of a “stable” lithium silicate that “protects” the silica from attack by the alkali and hydroxil ions.
- Presence of lithium ions would reduce the dissolution of silica from reactive material.
- Formation of a non-swelling lithium-based reaction product (gel)



Summary on Preventing AAR

- For assuring long-term performance of concrete infrastructures → risk of deleterious expansion and cracking in concrete due to AAR should be prevented
- Preventing ACR → reject the aggregate !!
- Preventing ASR:
  - » Use of non-reactive aggregates
  - » Use appropriate amount of fly ash (minimum 20-30% Class Fly ash), slag (minimum 35%) or combinations of the above (ternary systems !); better concrete !!
  - » Use appropriate amount of chemical admixture (e.g. $LiNO_3$) → aggregate type, long term ?, $$

Summary on Preventing AAR

Select preventive measures :

- **Prescriptive approach → risk analysis**
  - **Reactivity of the aggregate**
  - **Nature of the structure (includes. design life)**
  - **Exposure conditions**

- **Performance approach → testing in the laboratory**


Report on Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction

U.S. Department of Transportation
Federal Highway Administration

How and When to Repair AAR-affected Concrete Structure???

Selecting the right time and the right method for mitigation

Treat the cause →

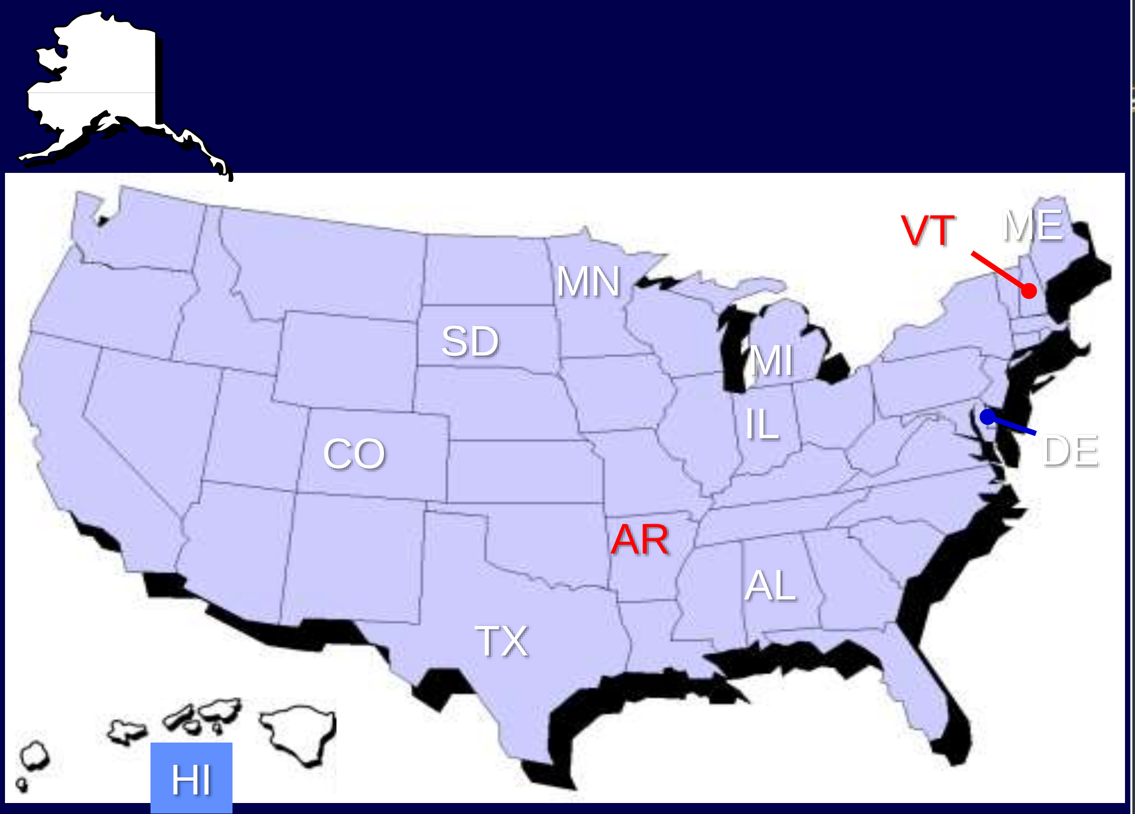
- Control of moisture
- Chemical treatments
- Strenghtening
- Stress relief

Humidity

Reactive silica, Alkalis

Control the effect → expansion

Evaluation of Mitigating measures in concrete structures affected by ASR (FHWA, USA)



U.S. Department of Transportation
Federal Highway Administration

Alkali-Silica Reactivity Development and Deployment Program

Selection, Implementation, and Evaluation of Field Application and Demonstration Projects

The Federal Highway Administration's (FHWA) Alkali-Silica Reactivity (ASR) Development and Deployment Program will focus on the use of different prevention and mitigation techniques for new and existing concrete pavements and structures. This effort will address the specific concrete durability distress mechanism of ASR. Through past research efforts, certain technologies now exist that may help prevent or mitigate the nation's ASR problem.

Electrochemical treatment on ASR-affected columns in Houston, TX

Under the ASR Development and Deployment program several field application and demonstration projects will be deployed to determine which technologies work best in preventing and mitigating ASR. FHWA will take the research "out of the lab" and deploy this knowledge in the field.

The FHWA will assist state departments of transportation (DOT) in executing ASR field trials by:

- Providing technical guidance (including presentations and training).
- Working together with the state DOT in selecting the appropriate treatment for the structure in question.
- Providing appropriate federal funds for prevention and mitigation techniques.
- Instrumenting the structure for data collection.
- Designing and implementing monitoring programs.
- Evaluating and collecting data from the field site, and
- Analyzing data to determine the efficacy of the technology used.

Pavement joint damage on an ASR-affected pavement near Mountain Home, ID (top); Vacuum impregnation treatment on ASR-affected highway barriers near Leominster, MA

Want your state to participate?

All efforts will be conducted in collaboration with state DOT personnel to ensure full implementation of the field trial. Appropriate funding will be provided by FHWA for selected projects.

For more details and requirements contact Gina Ahlstrom at gina.ahlstrom@dot.gov or at (202)366-4612.

ASTM (American Society for Testing and Materials) C1293 Laboratory

FEDERAL HIGHWAY ADMINISTRATION CONTACT

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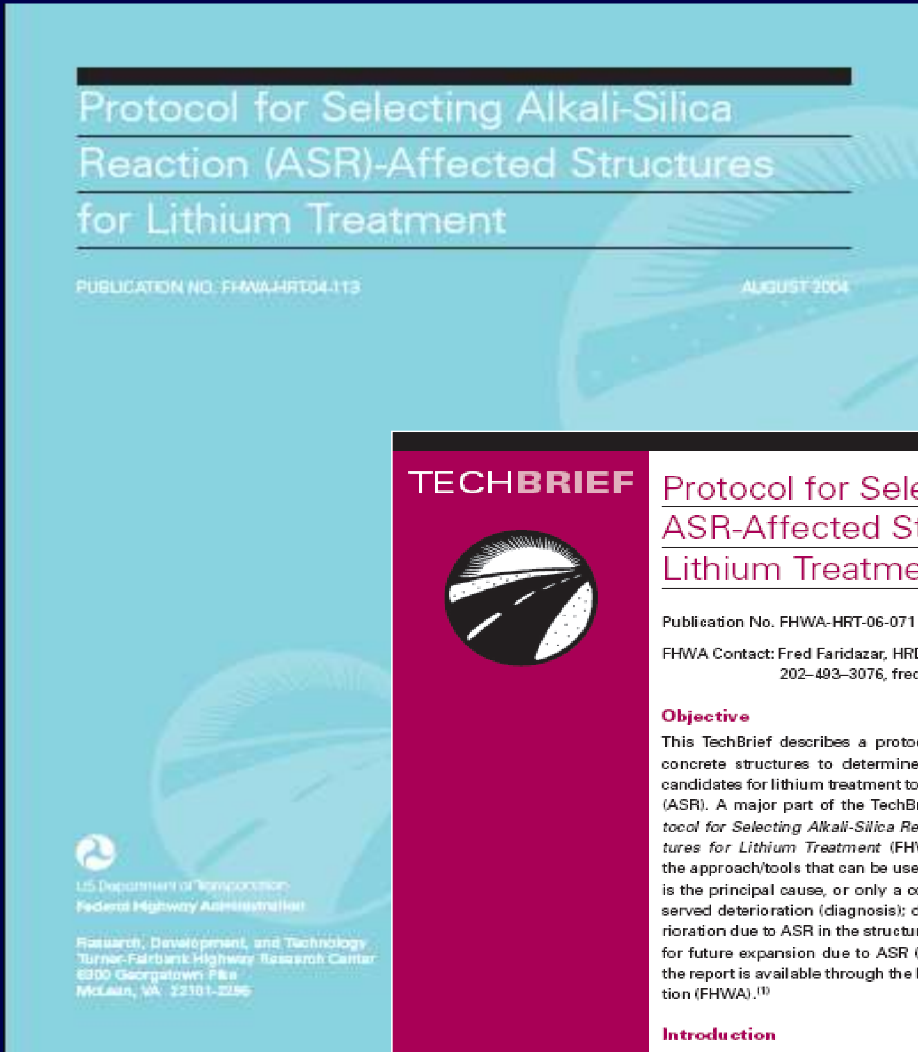
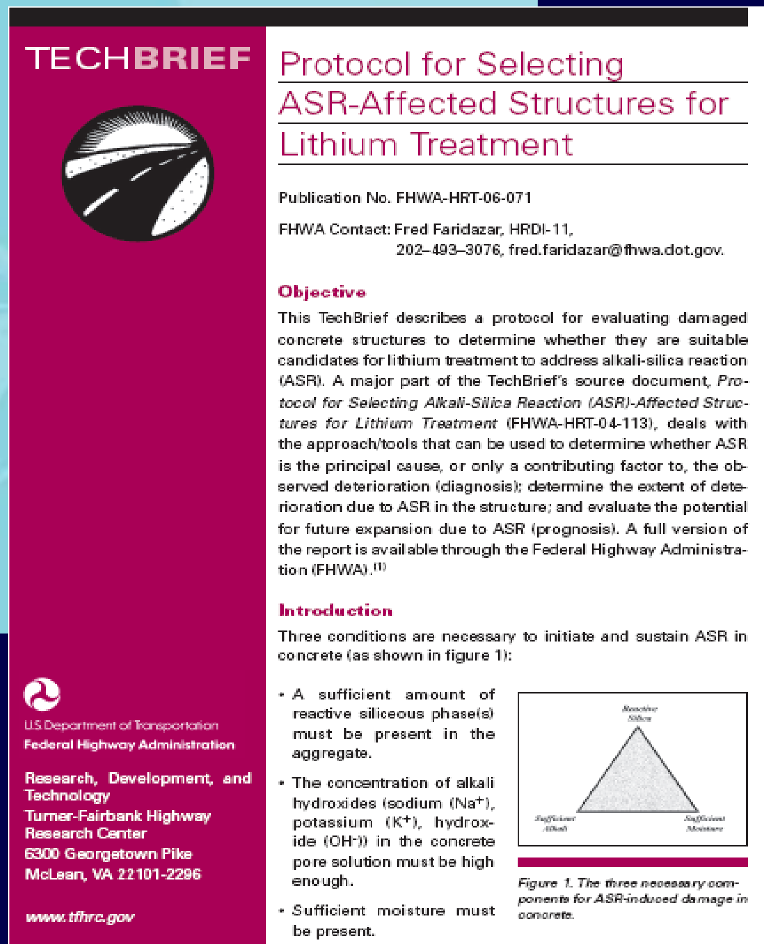


Protocol for Selecting Alkali-Silica Reaction (ASR)-Affected Structures for Lithium Treatment

PUBLICATION NO. FHWA-HRT-04-113 AUGUST 2004

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296



TECHBRIEF

Protocol for Selecting ASR-Affected Structures for Lithium Treatment

Publication No. FHWA-HRT-06-071

FHWA Contact: Fred Faridazar, HRDI-11, 202–493–3076, fred.faridazar@fhwa.dot.gov.

Objective

This TechBrief describes a protocol for evaluating damaged concrete structures to determine whether they are suitable candidates for lithium treatment to address alkali-silica reaction (ASR). A major part of the TechBrief's source document, *Protocol for Selecting Alkali-Silica Reaction (ASR)-Affected Structures for Lithium Treatment* (FHWA-HRT-04-113), deals with the approach/tools that can be used to determine whether ASR is the principal cause, or only a contributing factor to, the observed deterioration (diagnosis); determine the extent of deterioration due to ASR in the structure; and evaluate the potential for future expansion due to ASR (prognosis). A full version of the report is available through the Federal Highway Administration (FHWA).[1]

Introduction

Three conditions are necessary to initiate and sustain ASR in concrete (as shown in figure 1):

- A sufficient amount of reactive siliceous phase(s) must be present in the aggregate.
- The concentration of alkali hydroxides (sodium (Na^+), potassium (K^+), hydroxide (OH^-)) in the concrete pore solution must be high enough.
- Sufficient moisture must be present.

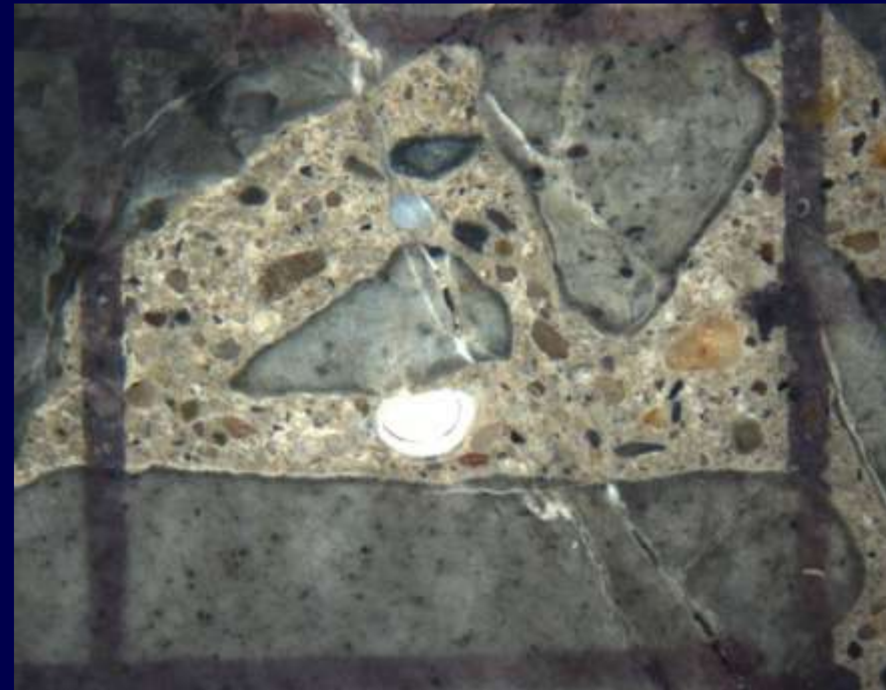
Figure 1. The three necessary components for ASR-induced damage in concrete.

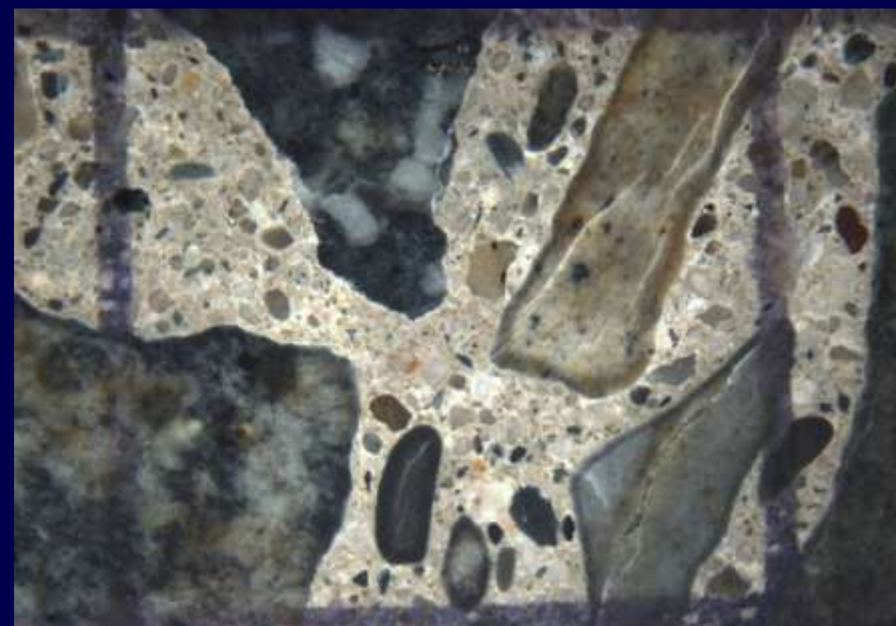
U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

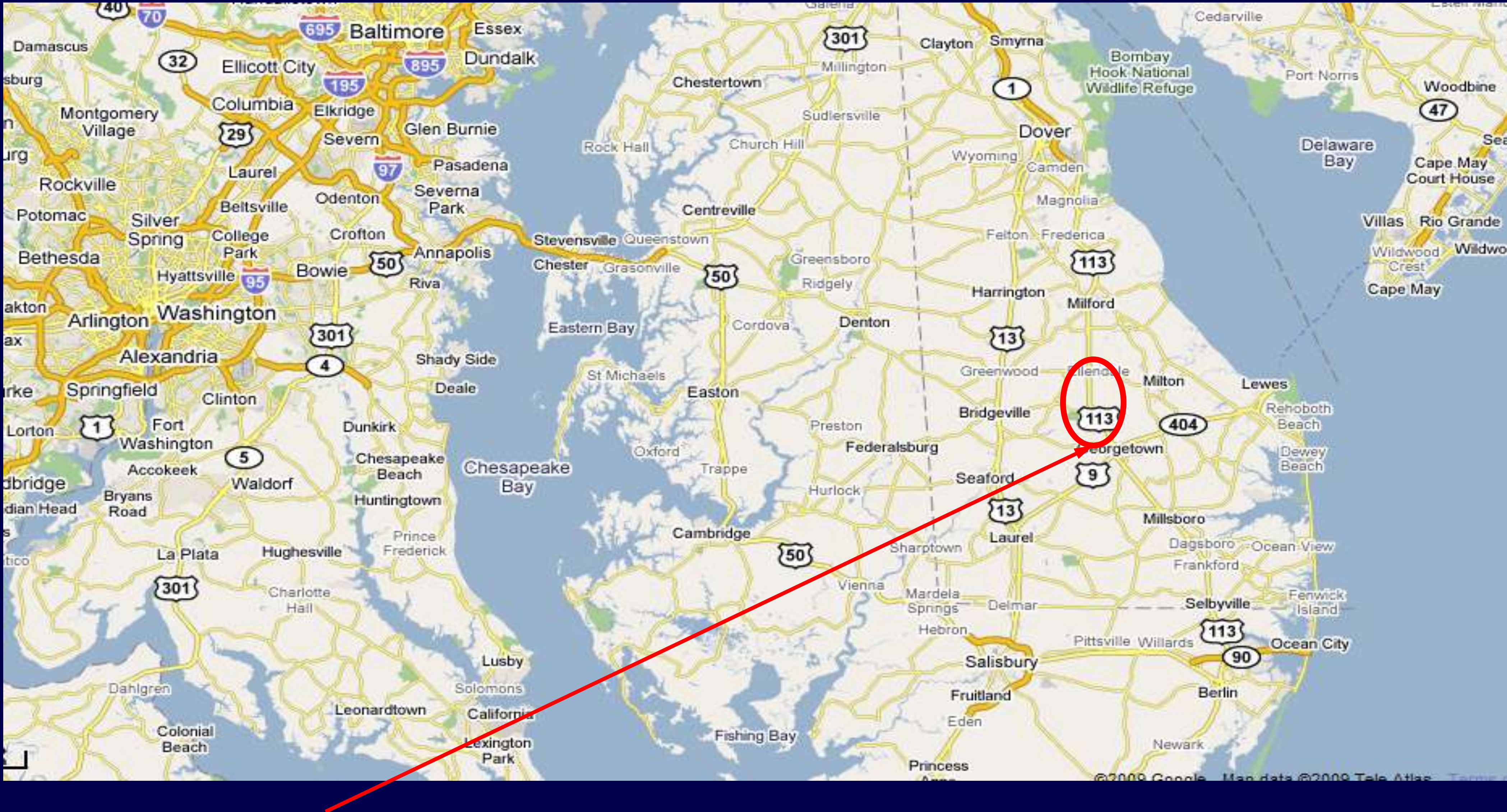
www.tfhrc.gov


OLYMPUS



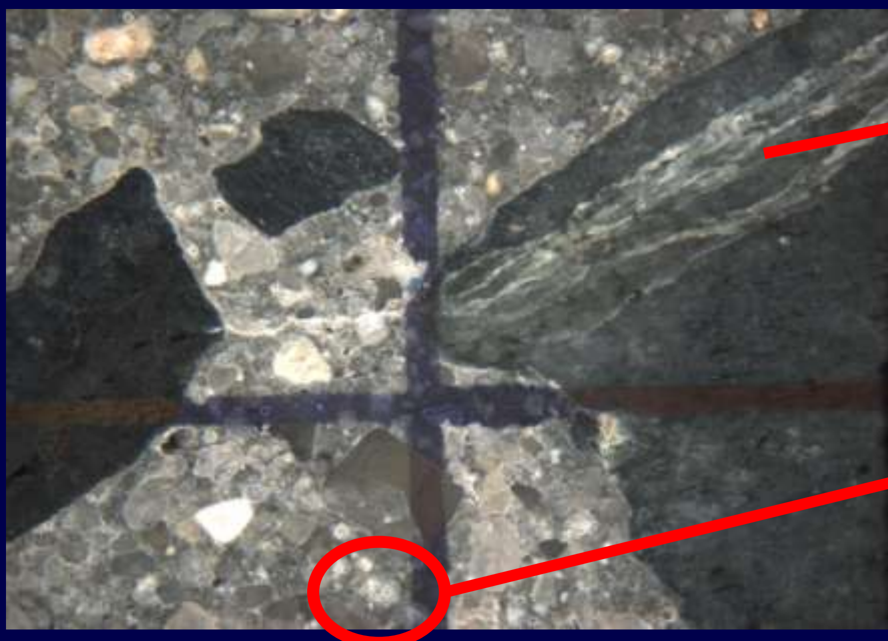


Georgetown – Delaware (June 23-25, 2009)

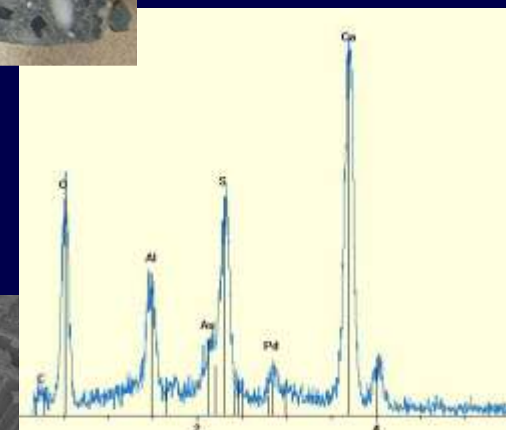


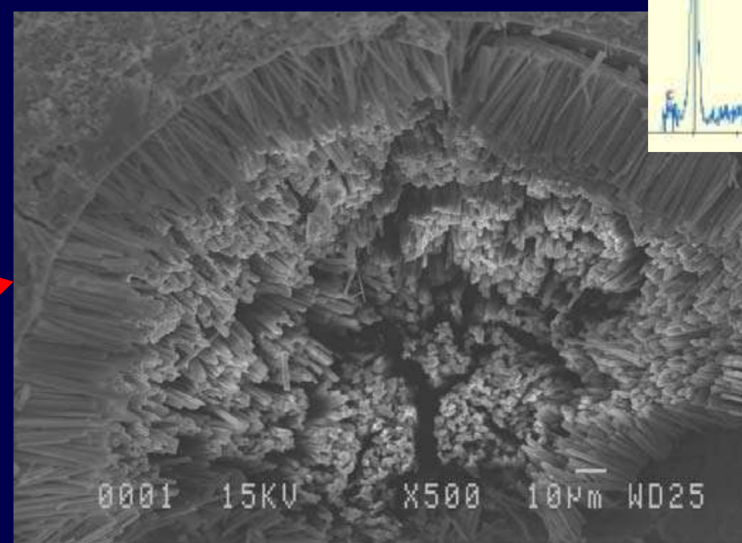
Highway 113 North of Georgetown

Concrete pavement (Delaware)



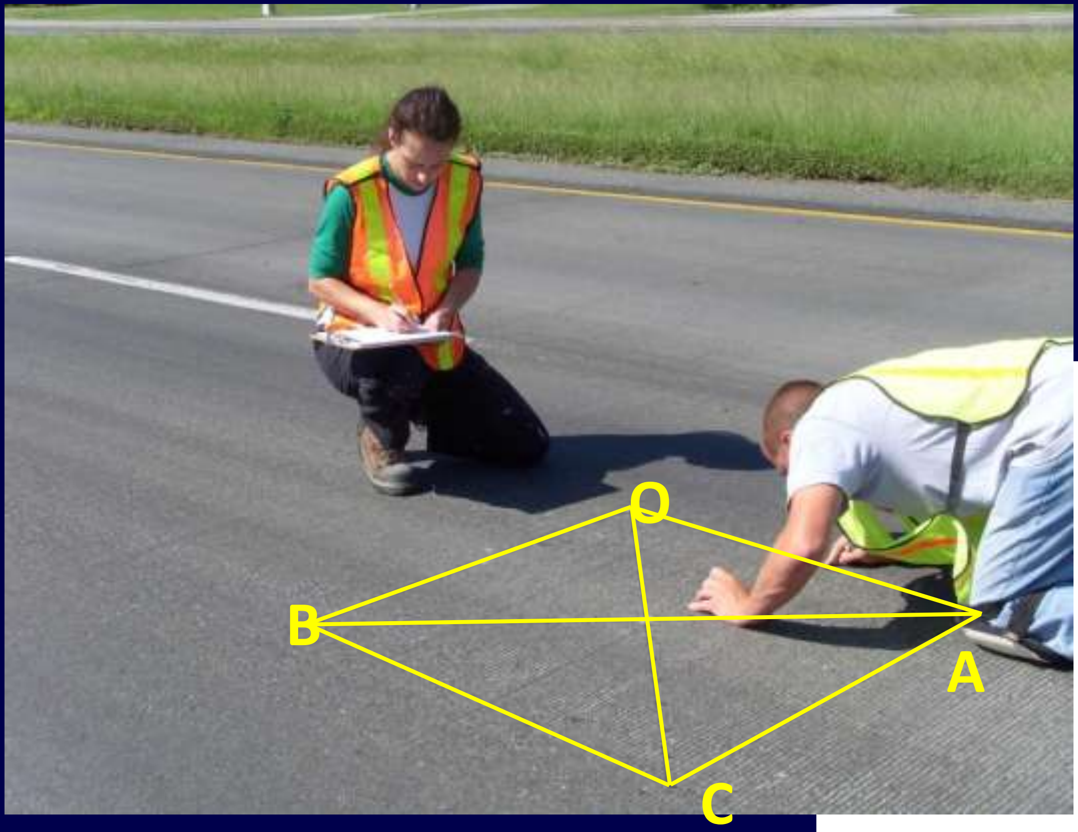
ASR

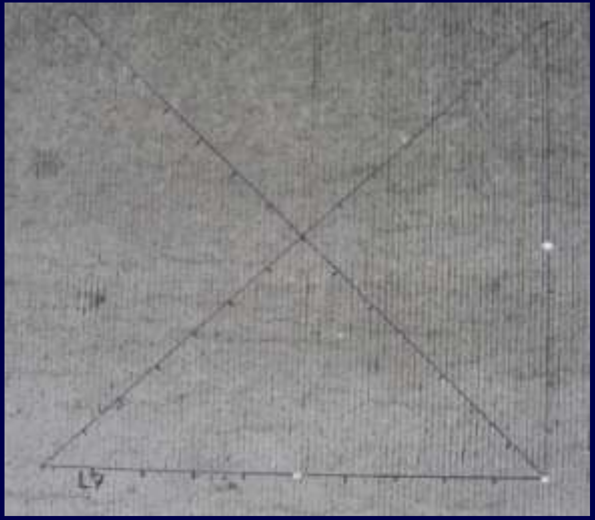


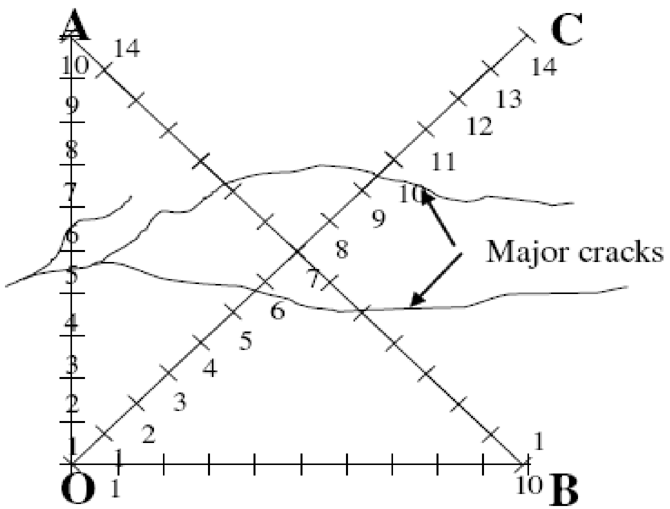


Ettringite

Monitoring efficacy in-situ → crack mapping







	1	2	3	4	5	Base length (m)	# cracks	Crack opening (mm)			
Interval	6	7	8	9	10			Total cumulative	Avg. / crack	Avg. / m	Global Average (CI)
	11	12	13	14							
OA	0.1, 0.1	0.8	--	--	1.9	1	6	4.8	0.8	4.8	3.39
	1.2	--	--	0.7	--						
OB	0.05	0.05	--	0.05	0.05	1	7	0.8	0.11	0.8	
	--	0.3	0.2	0.1	--						
OC	--	--	0.3, 0.5	0.4	0.3	1.4	7	5.6	0.8	4.0	
	1.4	0.3	--	--	2.4						
	--	--	--	--							
AB	0.5	0.2	--	--	0.3	1.4	8	5.05	0.63	3.6	
	0.05	1.5	0.1, 0.2	--	2.2						
	--	--	--	--							

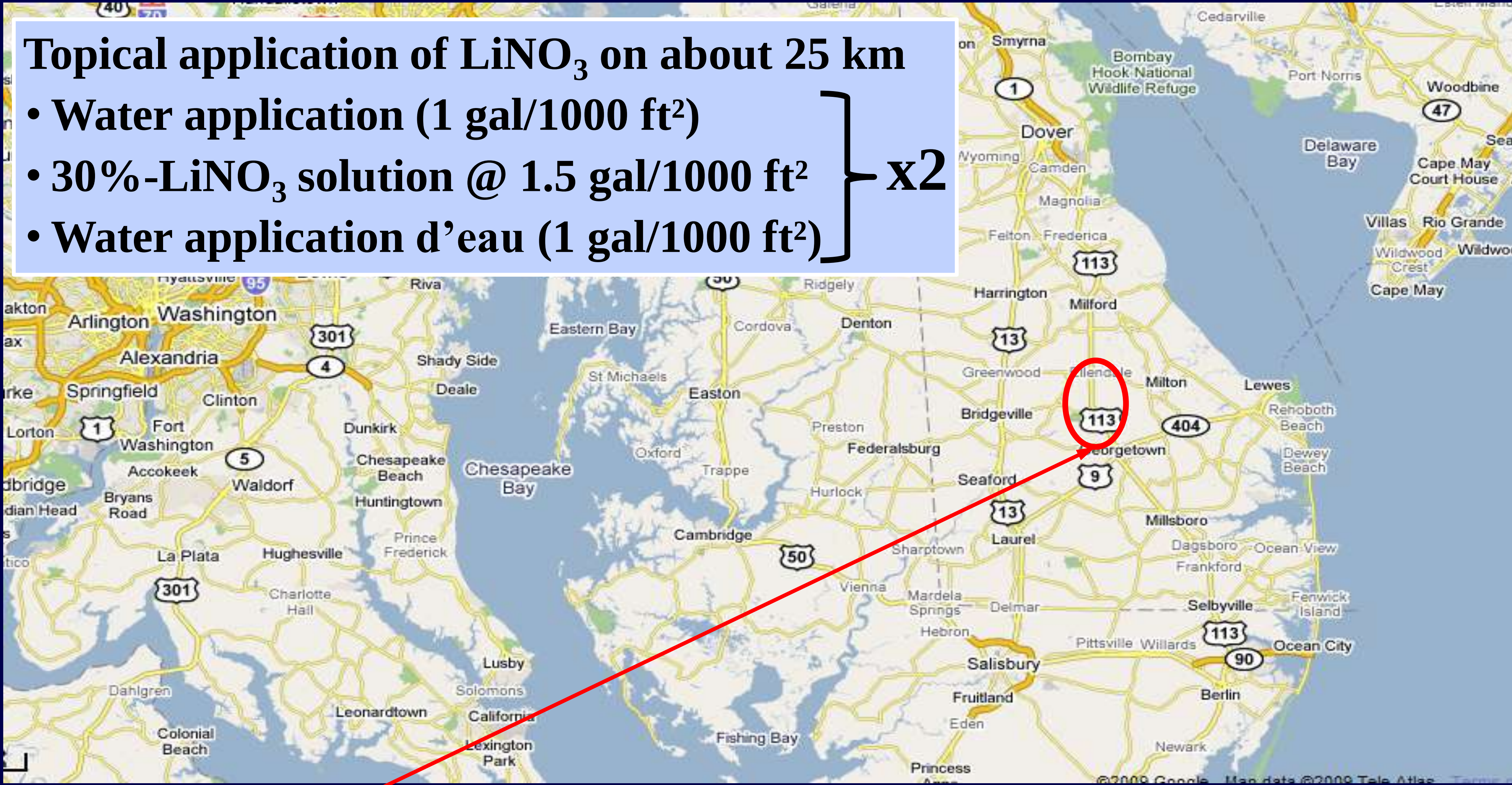
Dimensional changes measurements

Georgetown – Delaware (June 23-25, 2009)

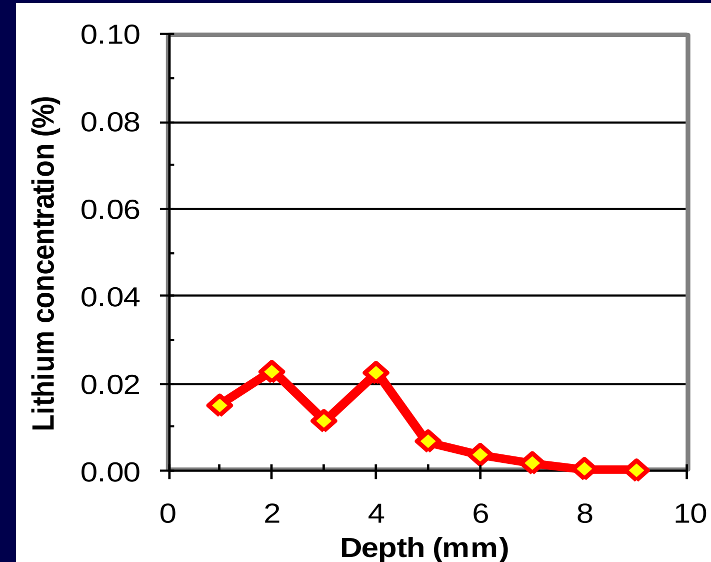
Topical application of $LiNO_3$ on about 25 km

- **Water application (1 gal/1000 ft^2)**
- **30%-$LiNO_3$ solution @ 1.5 gal/1000 ft^2**
- **Water application d'eau (1 gal/1000 ft^2)**

x2



Highway 113 North of Georgetown



Treatment → $LiNO_3$ application (3 gal / 1000 ft^2) → limited penetration depth

Maine: I395 (Bangor / Brewer)

I395 over Main

I395 over Penobscot River

5th Parkway (Robertson) over I395

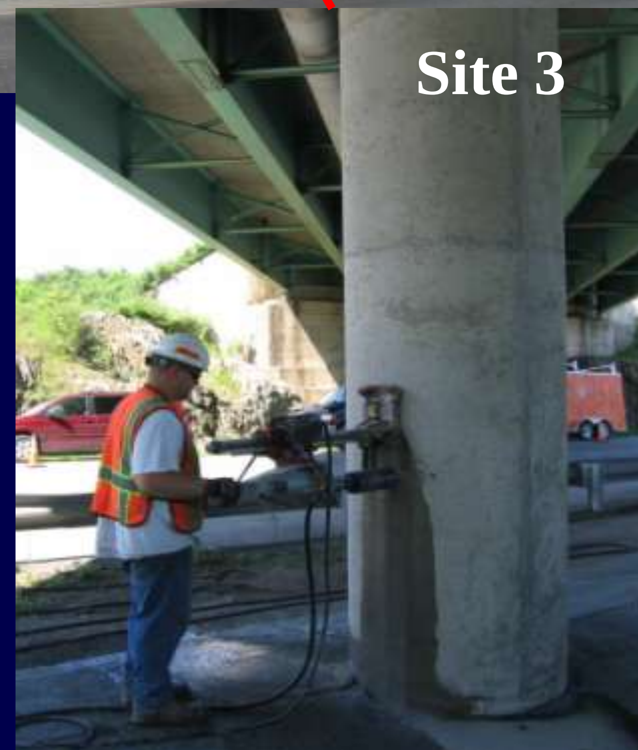
South Parkway over I395

Green Point Road over I395

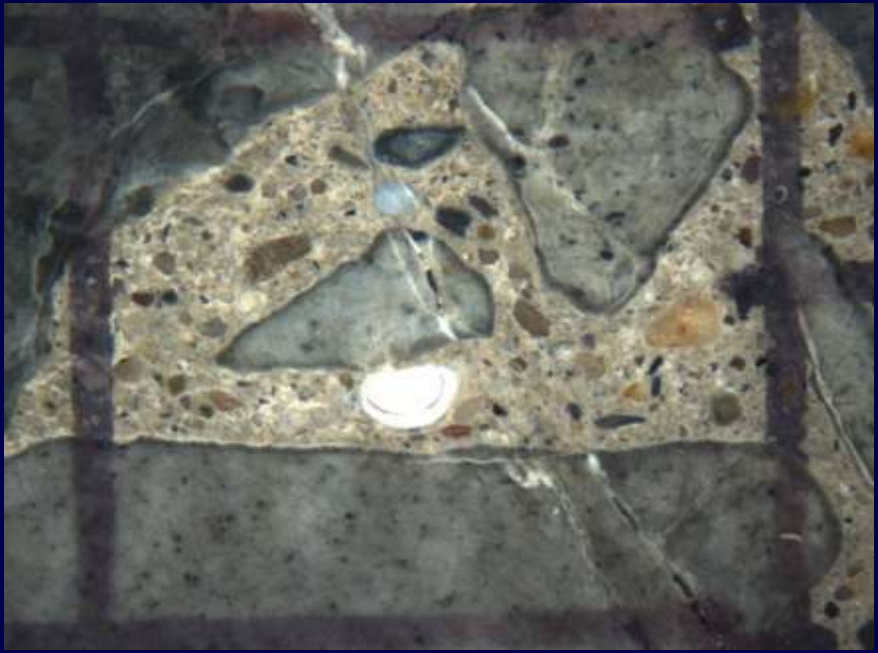
Rte 1A over 395

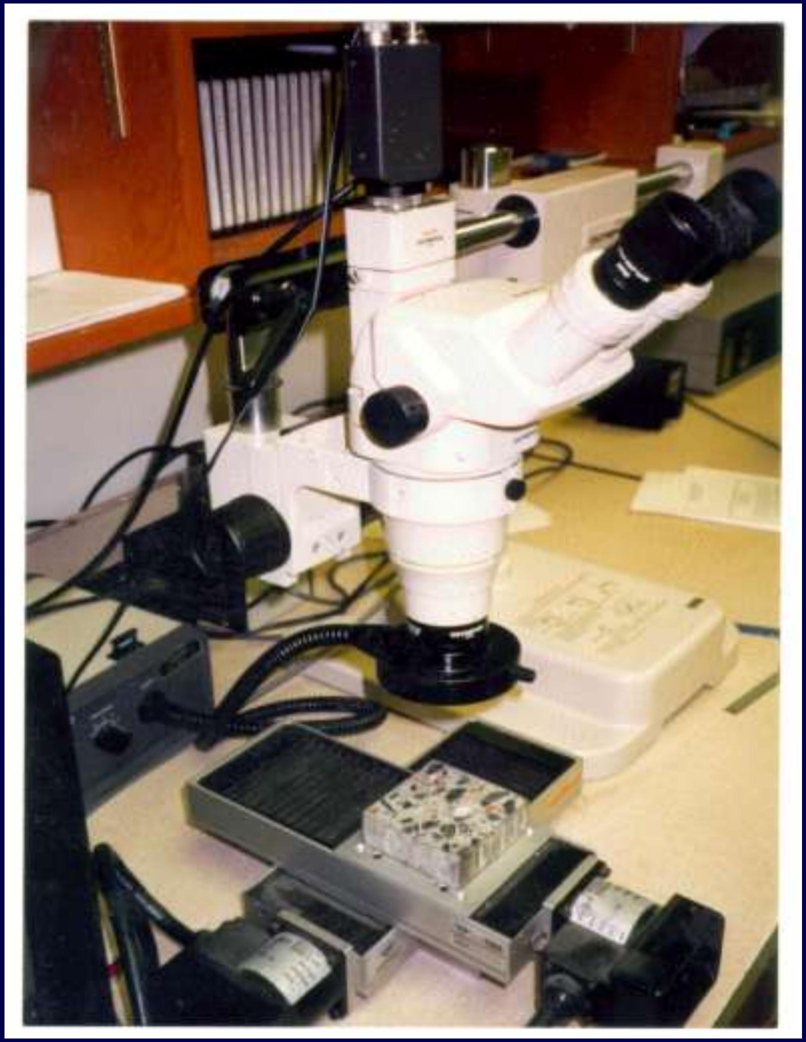
Rte 1A over railroad

South Parkway over I 395



Damage Rating Index (DRI)



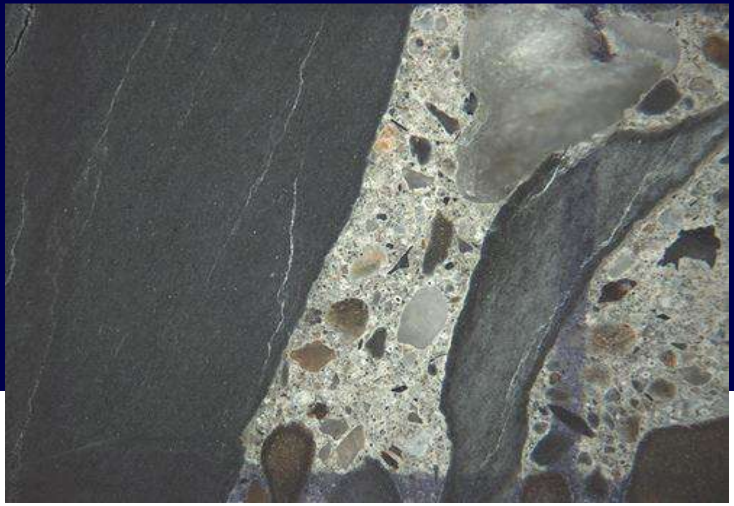


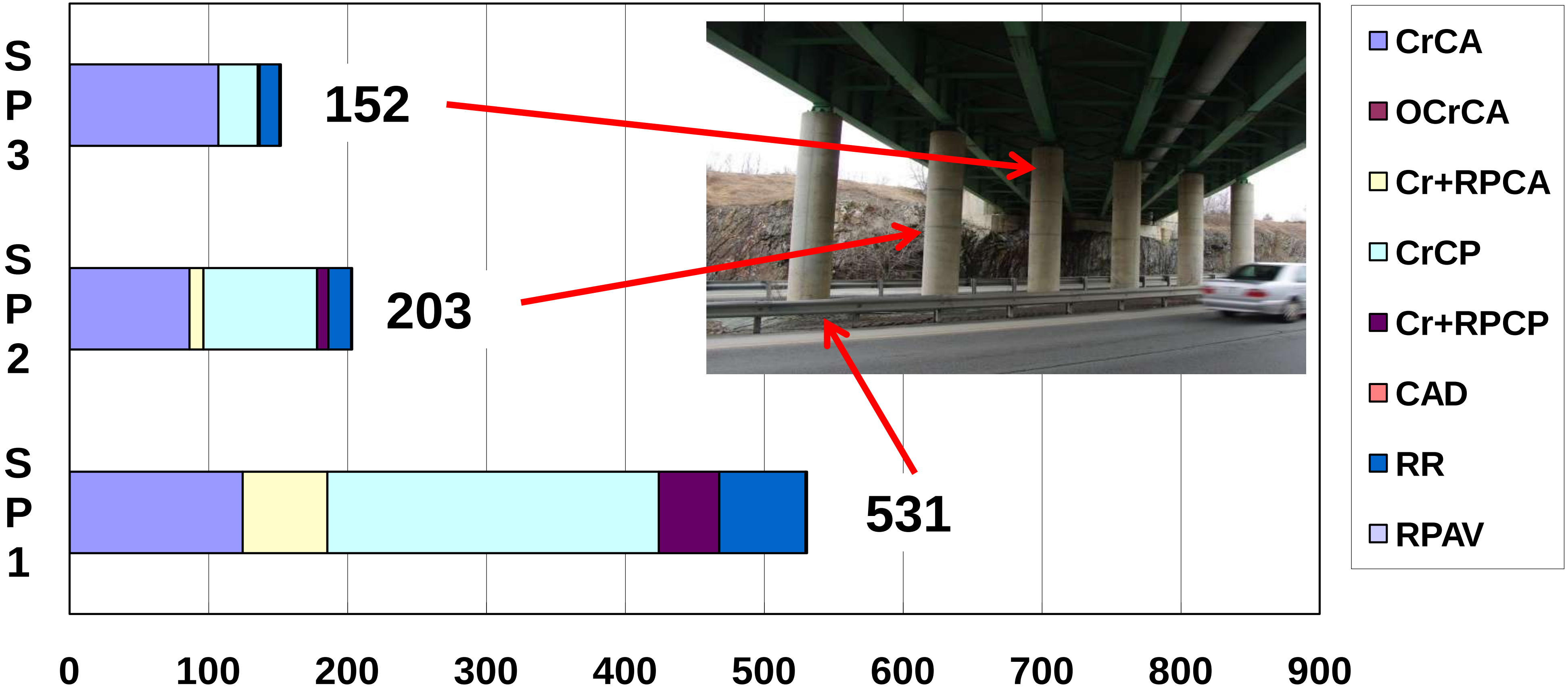
ASR Petrographic Features & Associated Factors

Petrographic feature	Abbreviation	Factor
Coarse aggregate with crack	CA	0.25
Open crack in coarse aggregate	OCA	4
Coarse aggregate with crack and gel	CA+G	2
Debonding coarse aggregate	DCA	3
Reaction rim	RR	0.5
Cement paste with crack	CP	2
Cement paste with crack and gel	CP+G	4
Gel in air void	V+G	0.5

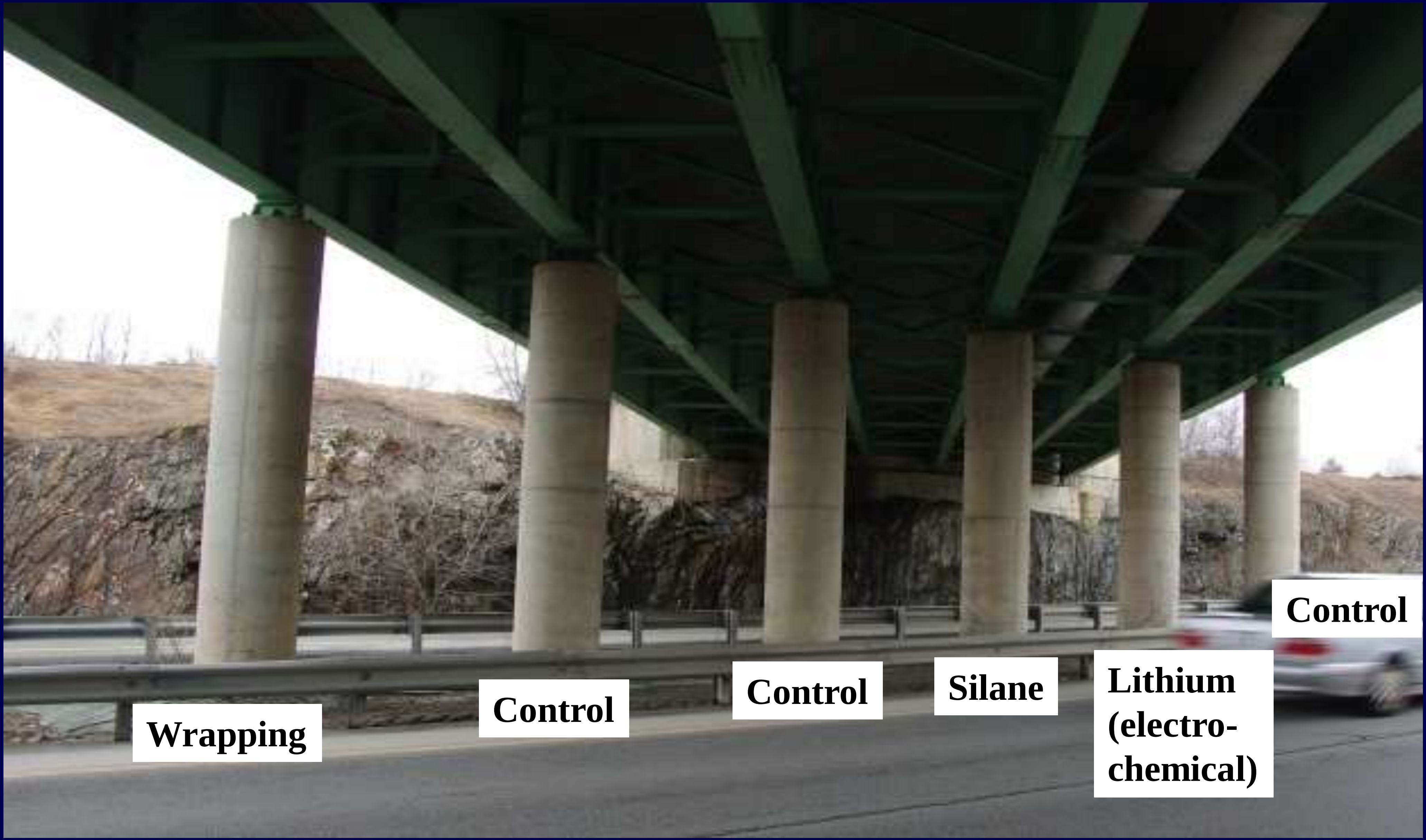
Grattan-Bellew and Danay (1992)

South Parkway over I 395





South Parkway over I395



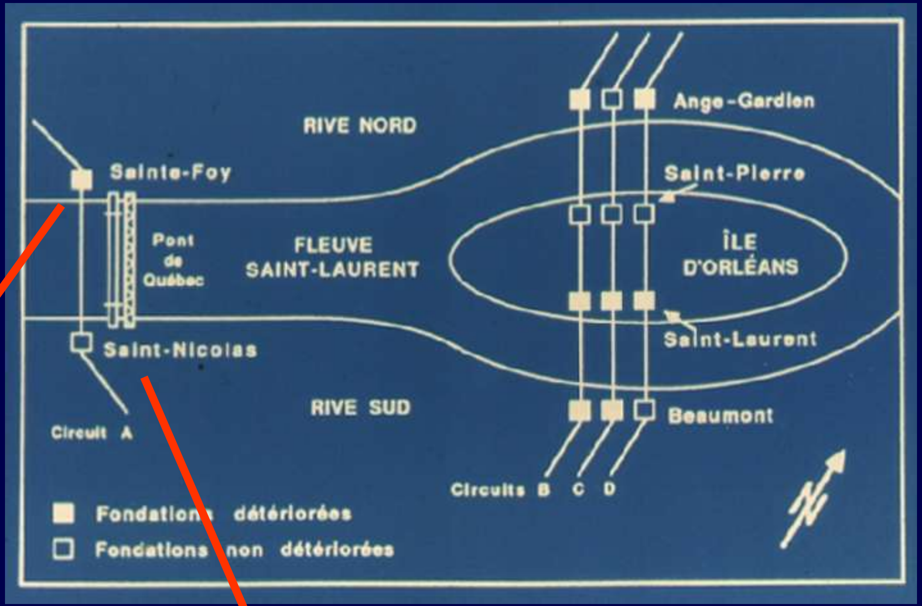
South Parkway over I395

Electrochemical treatment ($LiNO_3$)

South Parkway over I395

Wrapping

Hydro-Québec
Electrical towers
Québec City



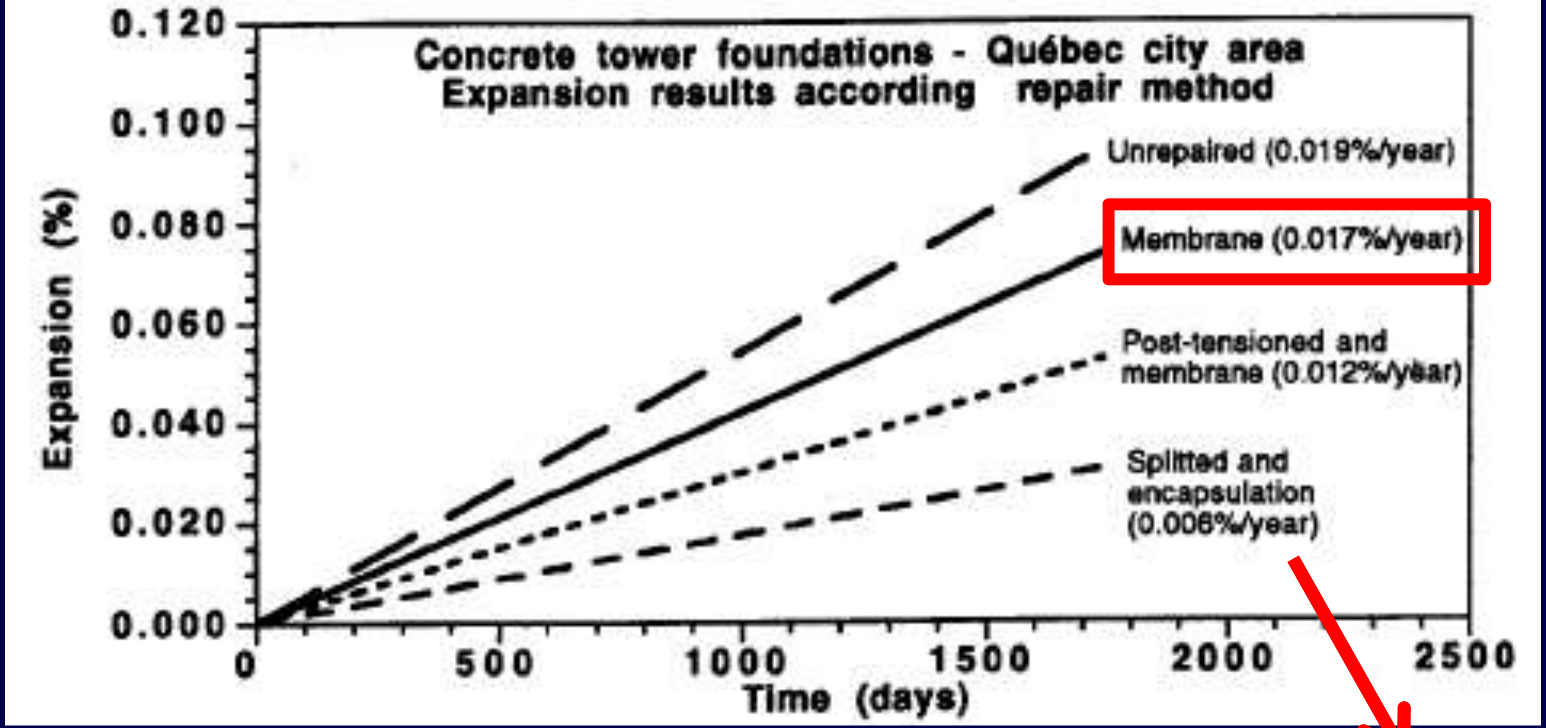
Hydro-Québec Electrical towers Québec City

- **Symptoms of deterioration**





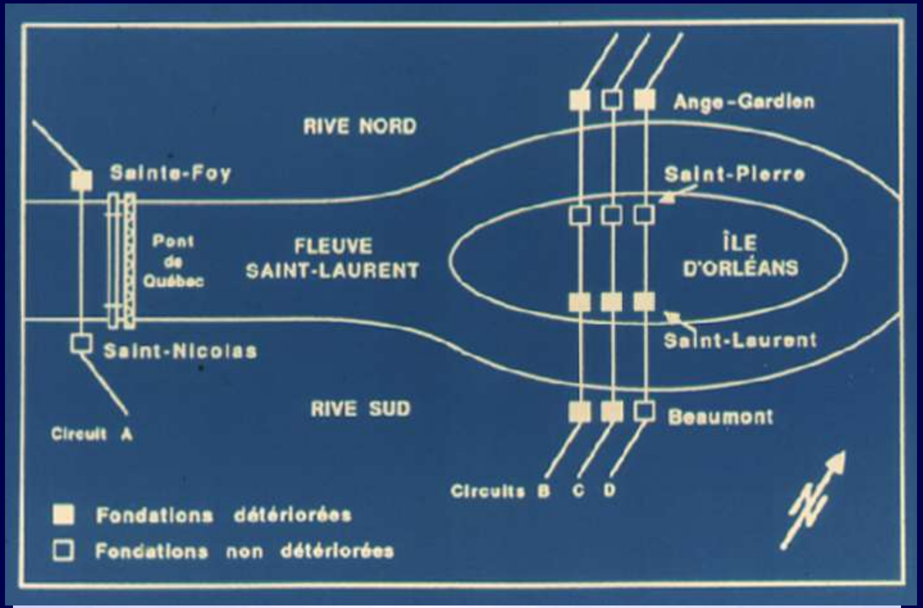



Concrete tower foundations - Québec city area
Expansion results according repair method
Unrepaired (0.019%/year)
Membrane (0.017%/year)
Post-tensioned and membrane (0.012%/year)
Splitted and encapsulation (0.006%/year)
Expansion (%)
0.120
0.100
0.080
0.060
0.040
0.020
0.000
0
500
1000
1500
2000
2500
Time (days)

(Durand 2000)

Management Actions on AAR Affected Concrete Structures

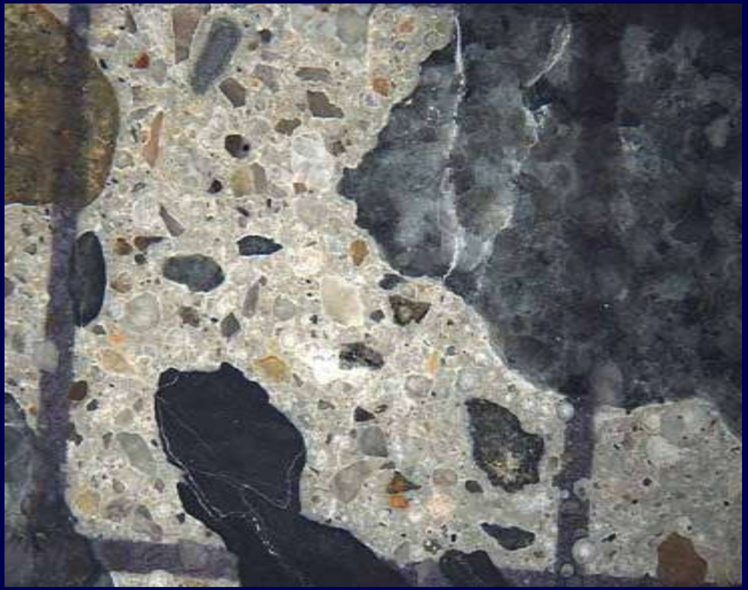
- Hydro-Québec
  Electrical towers
  Québec City

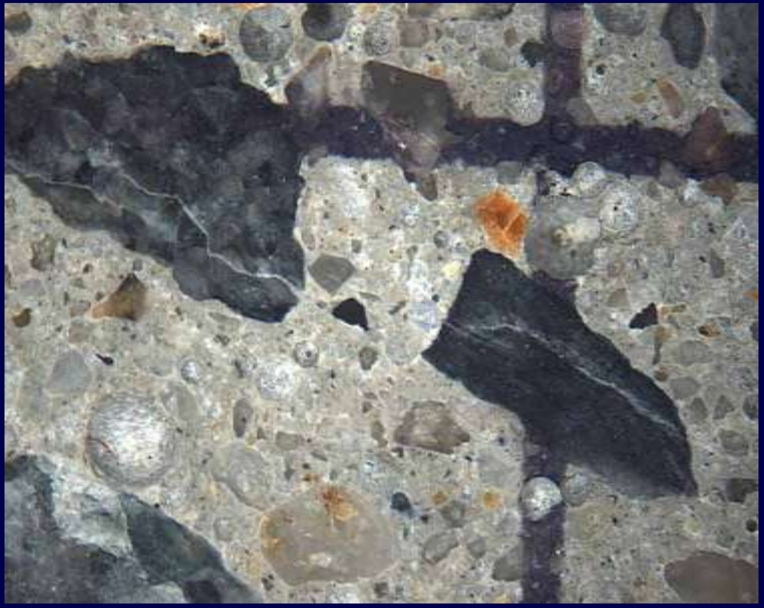


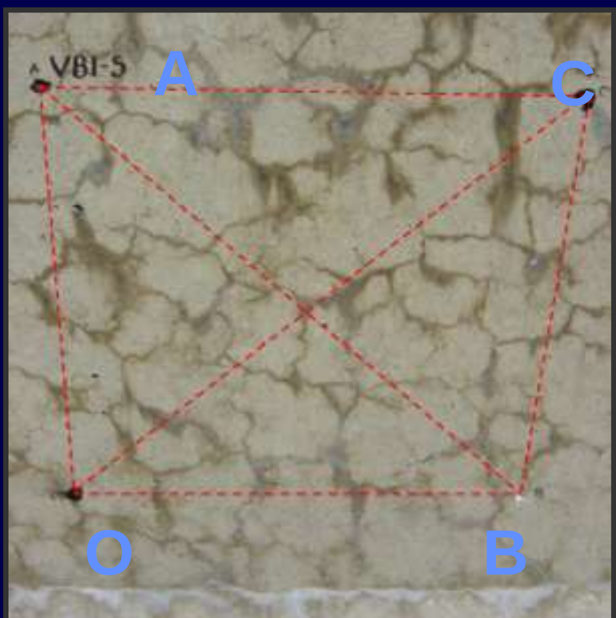
1990

2009

Median (Jersey) barriers, Leominster, MA





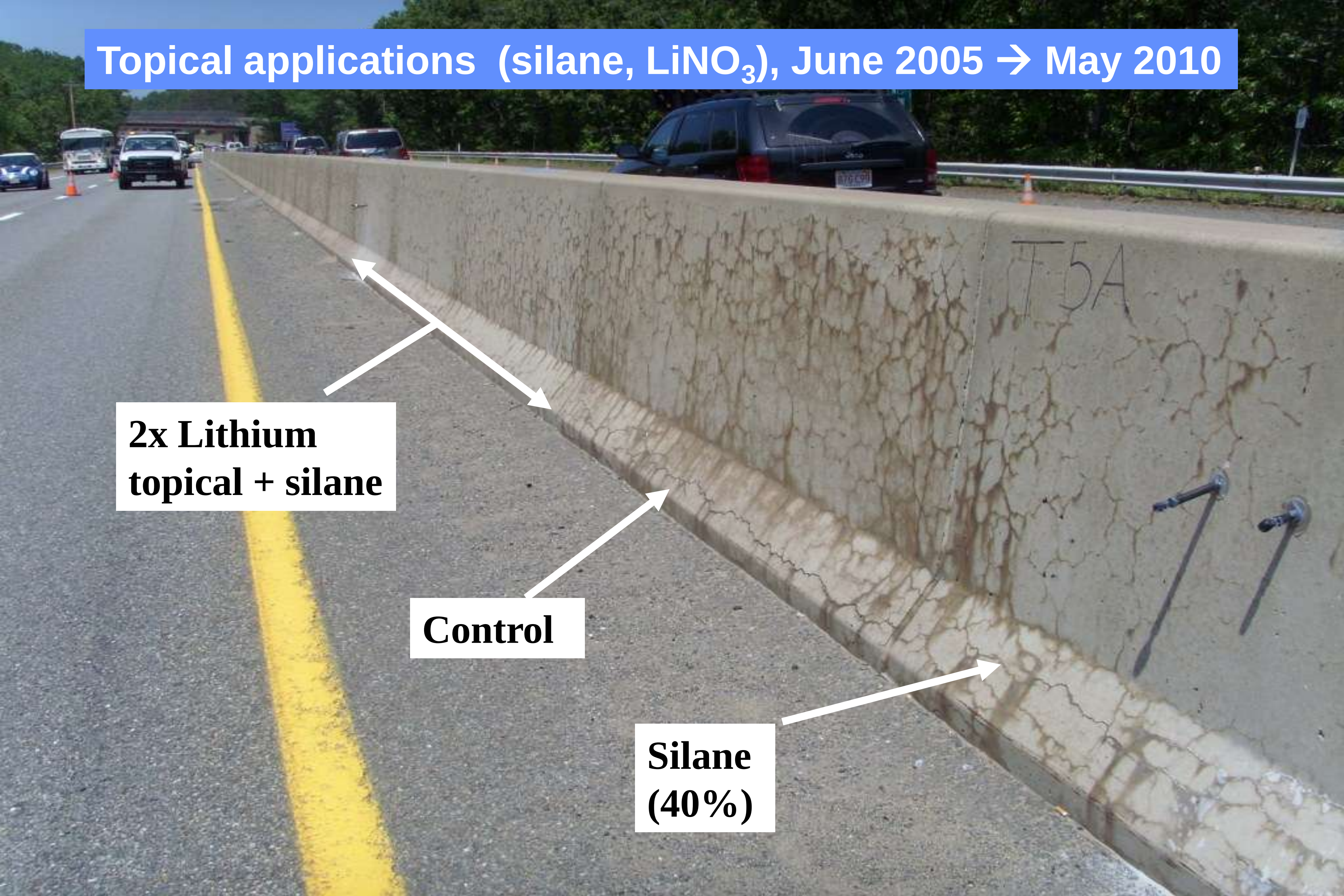

VBI-5
A
C
O
B

Median (Jersey) barriers, Leominster, MA

- Control sections
- Vacuum impregnation ($LiNO_3$)
- Topical application (silane, $LiNO_3$)

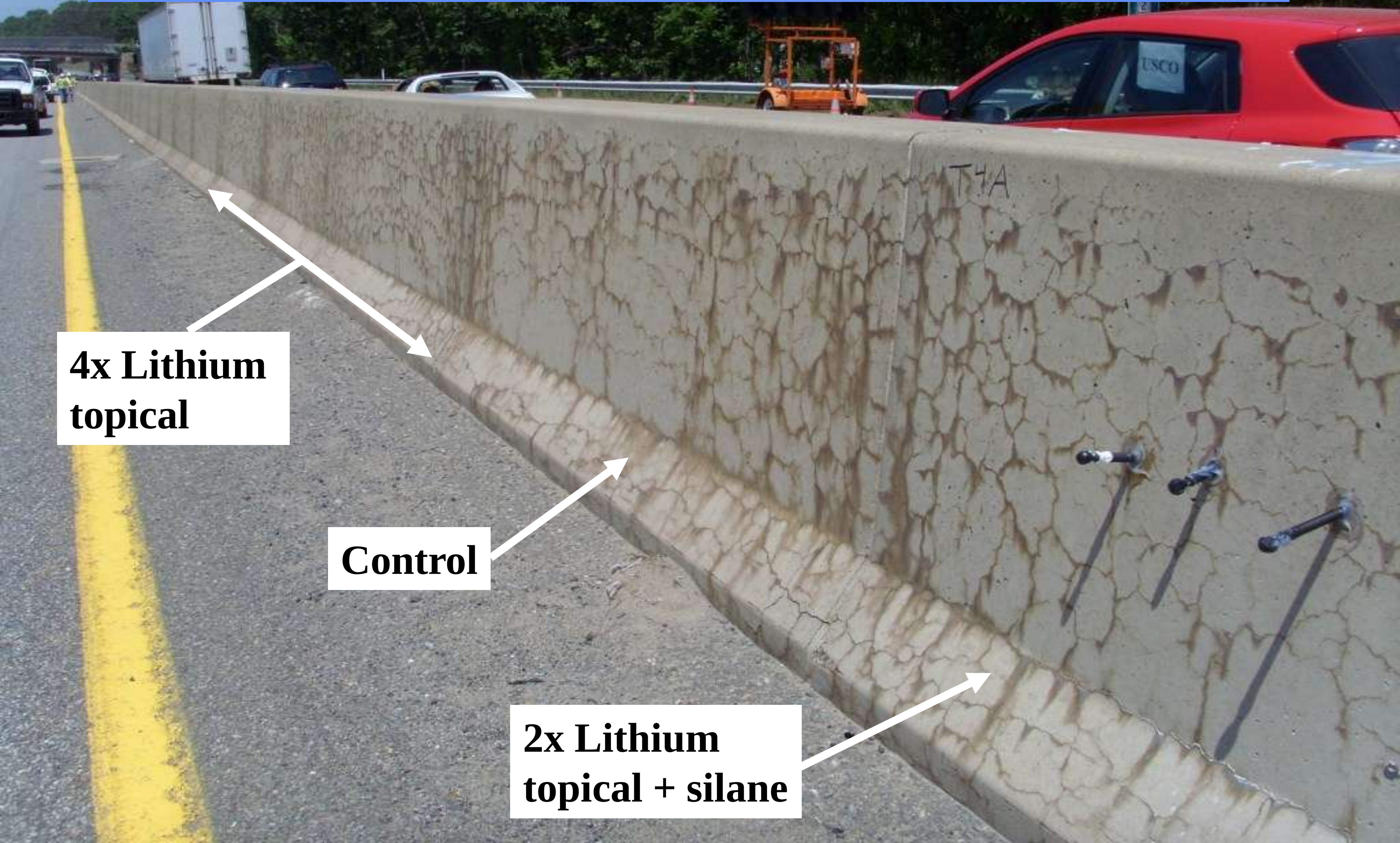
Median (Jersey) barriers → vacuum impregnation

Median (Jersey) barriers → topical application (silane, $LiNO_3$)



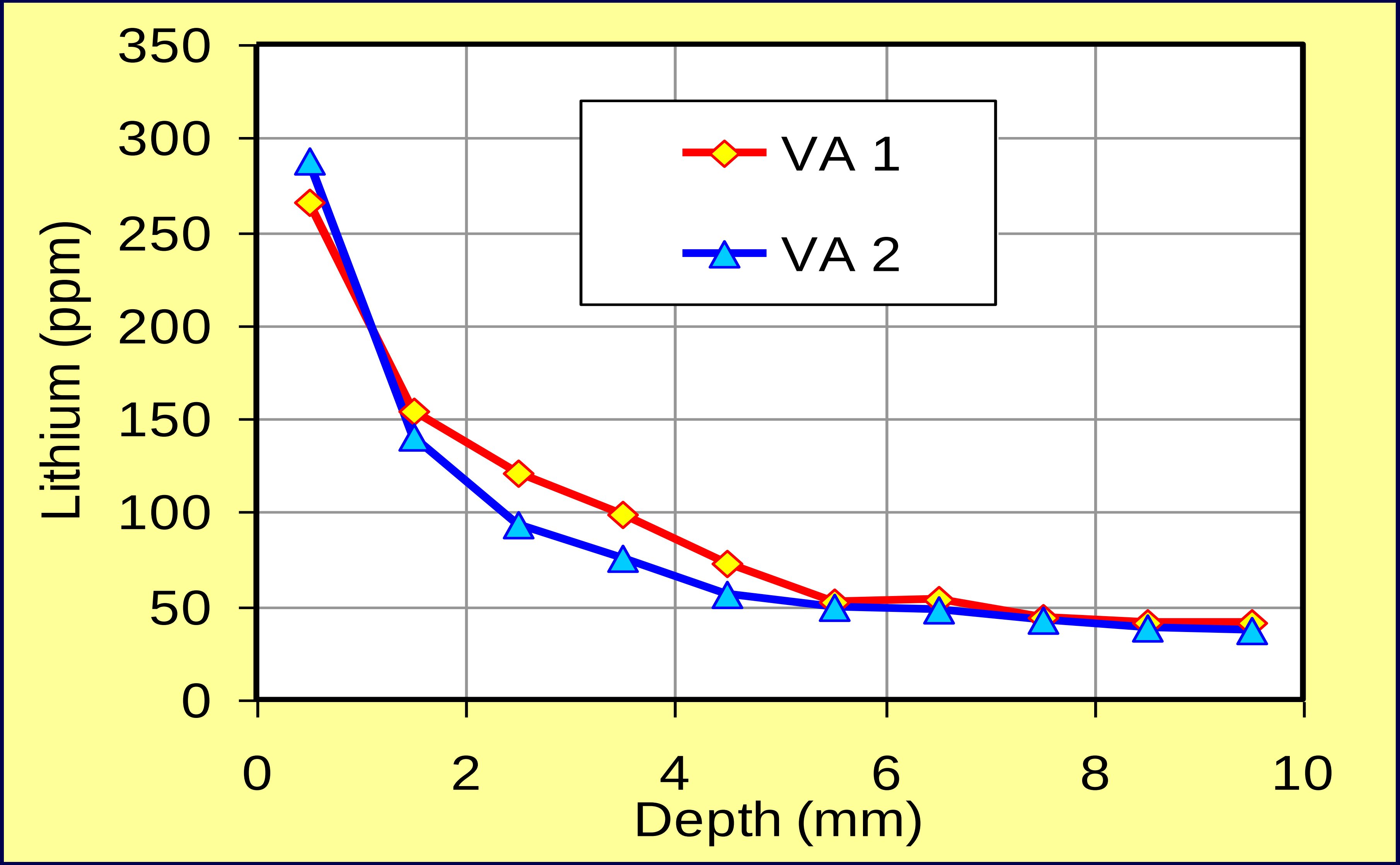
Topical applications (silane, $LiNO_3$), June 2005 → May 2010
2x Lithium topical + silane
Control
Silane (40%)
T5A

Topical applications (silane, $LiNO_3$), June 2005 → May 2010

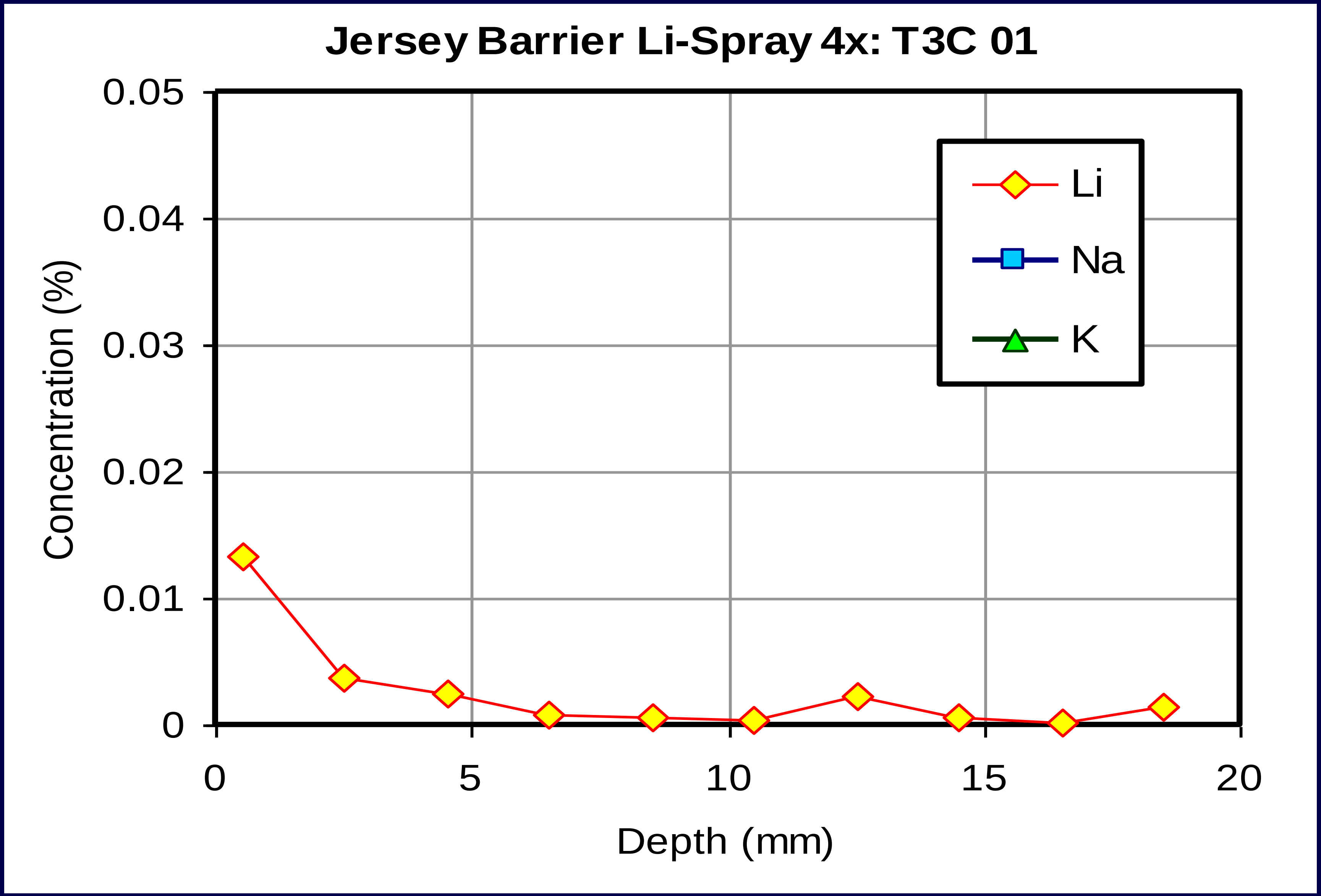


Median (Jersey) barriers → sampling (Li profiling)

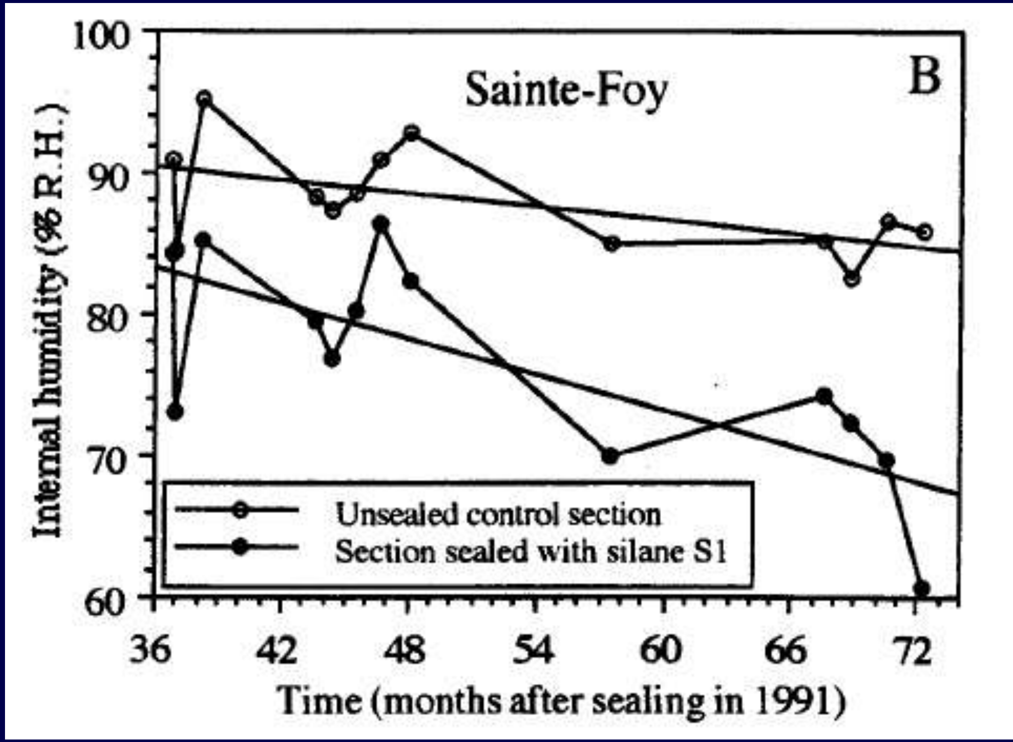
Median (Jersey) barriers → efficacy vacuum treatment



Median (Jersey) barriers → 4 $LiNO_3$ topical treatments

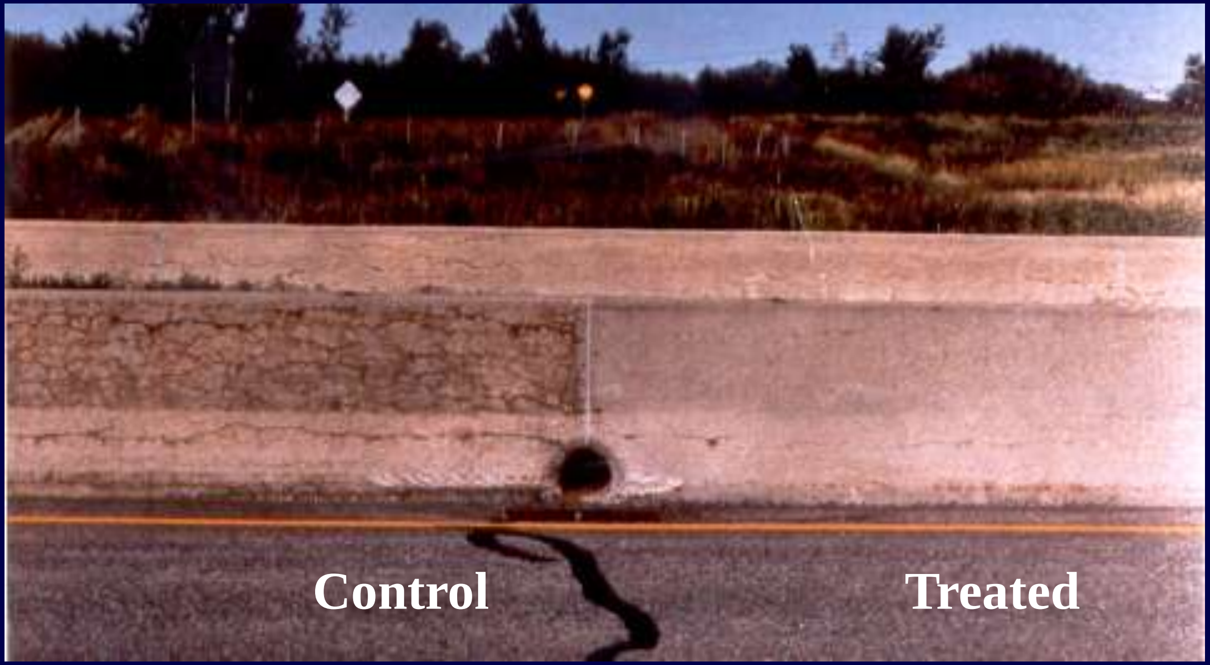


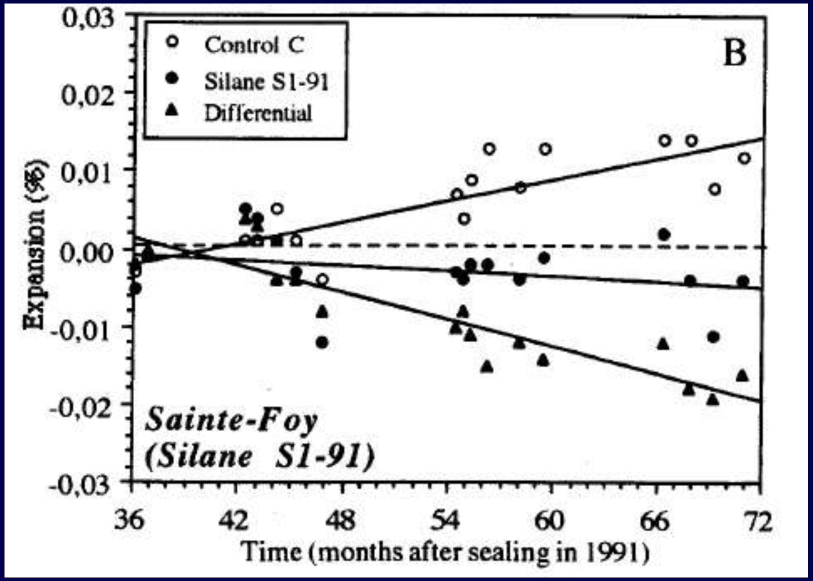
Use of Sealers (Quebec City, Canada) – early 1990's



Courtesy of M.A. Bérubé

early 1990's

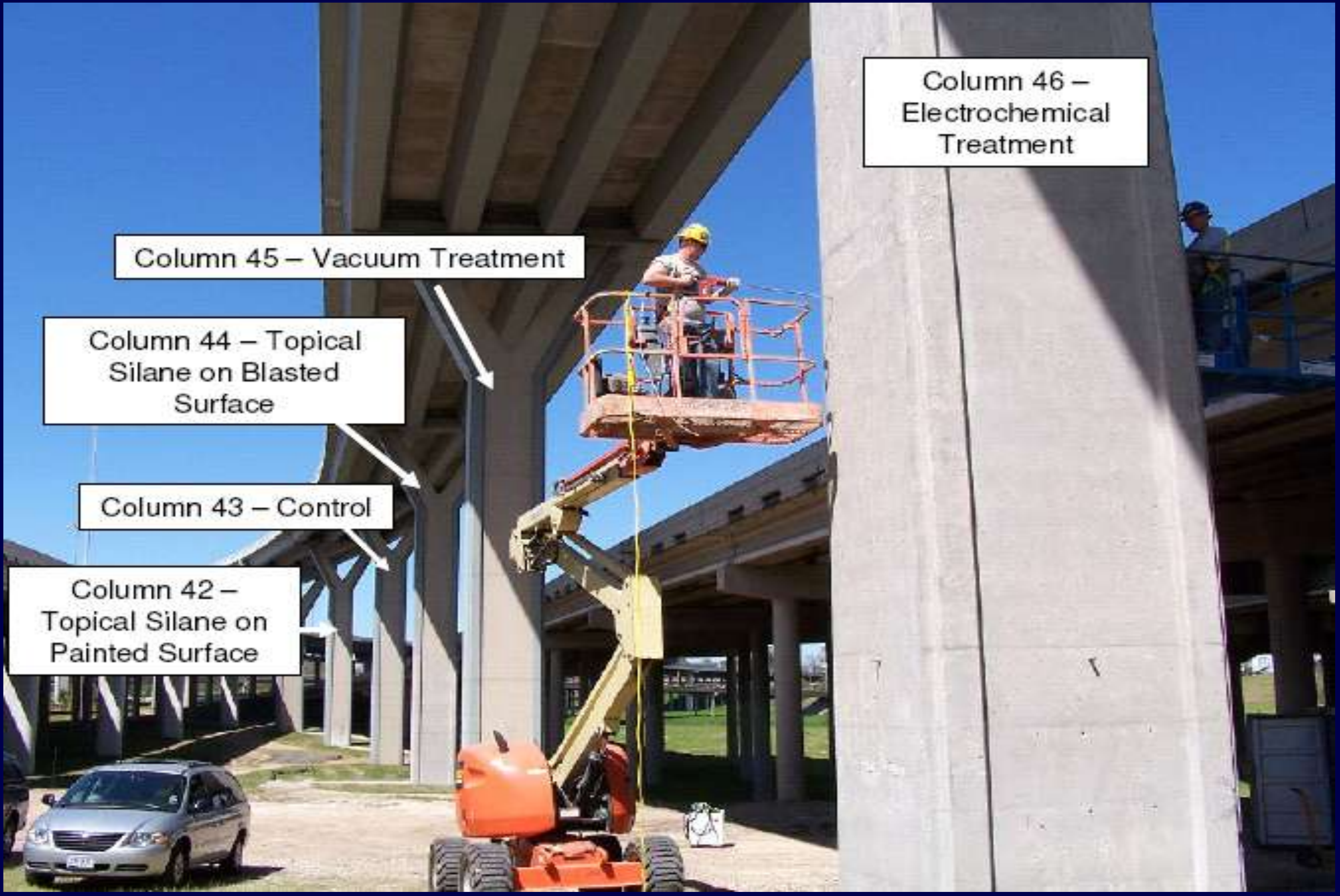




Courtesy of M.A. Bérubé

2008

Bridge structure – Houston, TX (USA) (2005)

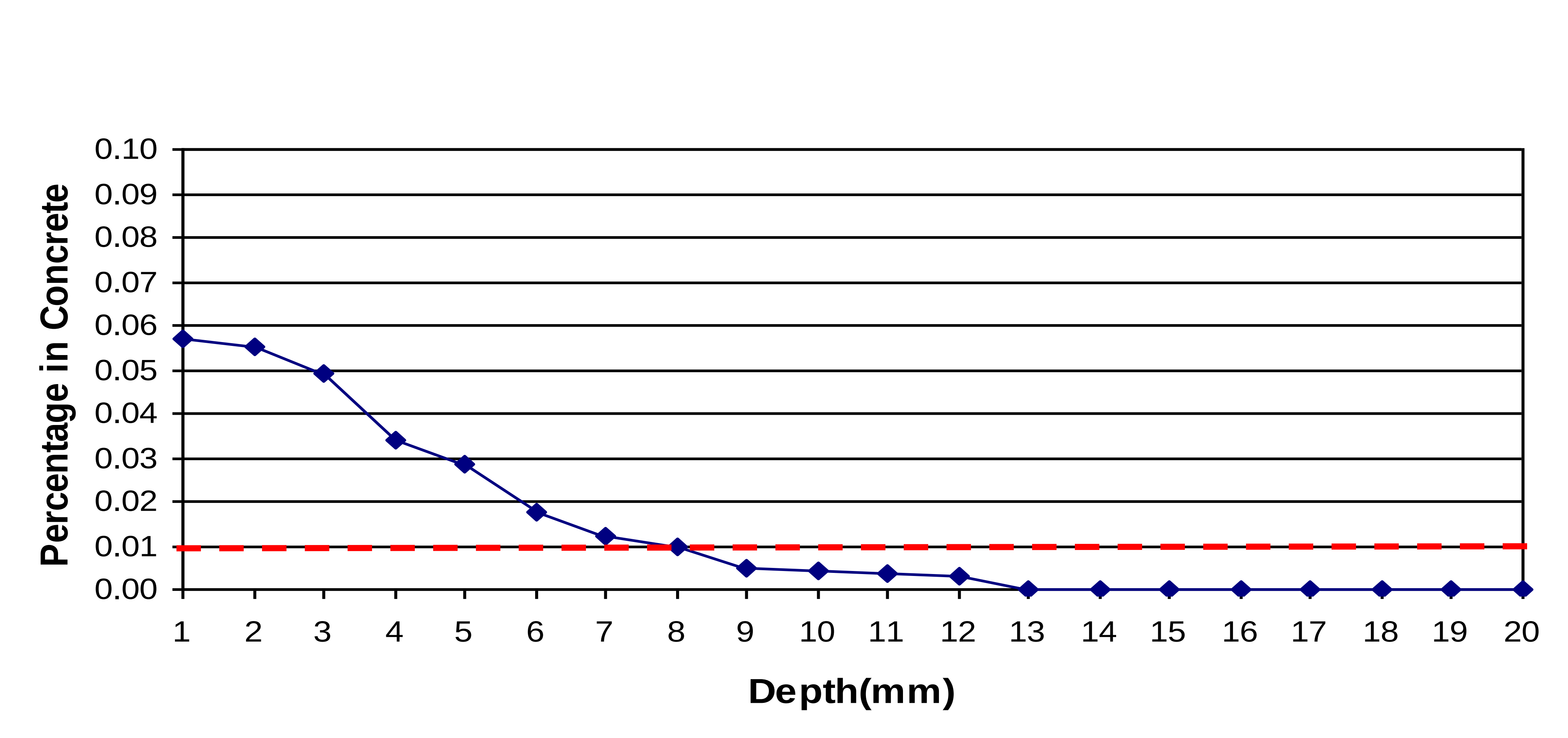




Vacuum impregnation $LiNO_3$

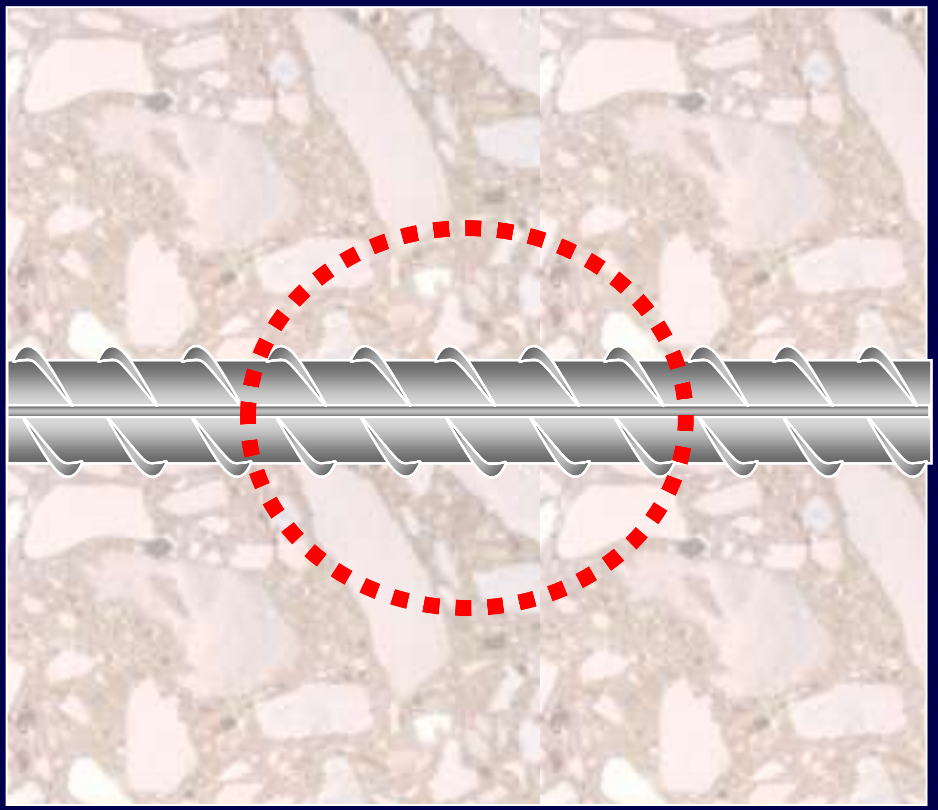
Electrochemical treatment

Column #45
Penetration depth after vacuum treatment

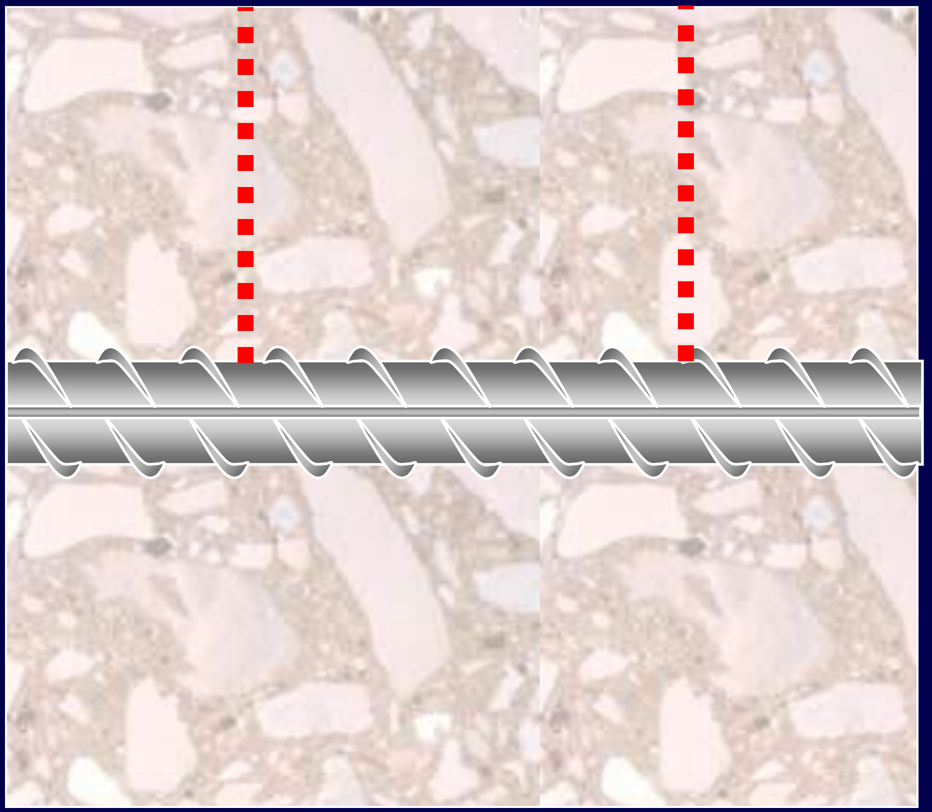


Column #46-1 - Electrochemical treatment

8-week treatment before sampling over rebars

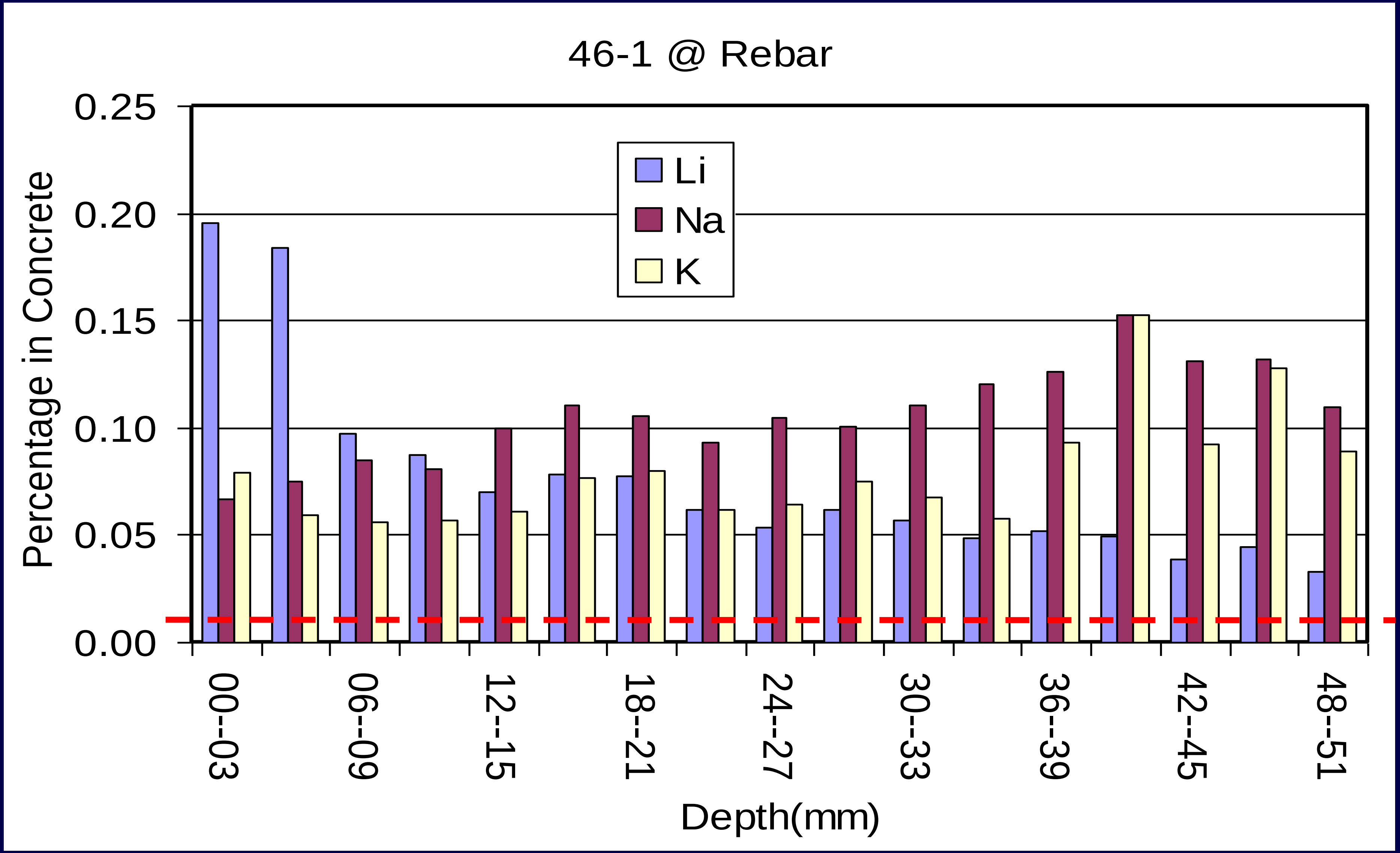


Plan



Profile

Profiles for Li, Na & K ions in the column (electrochemical treatment)



Conclusions

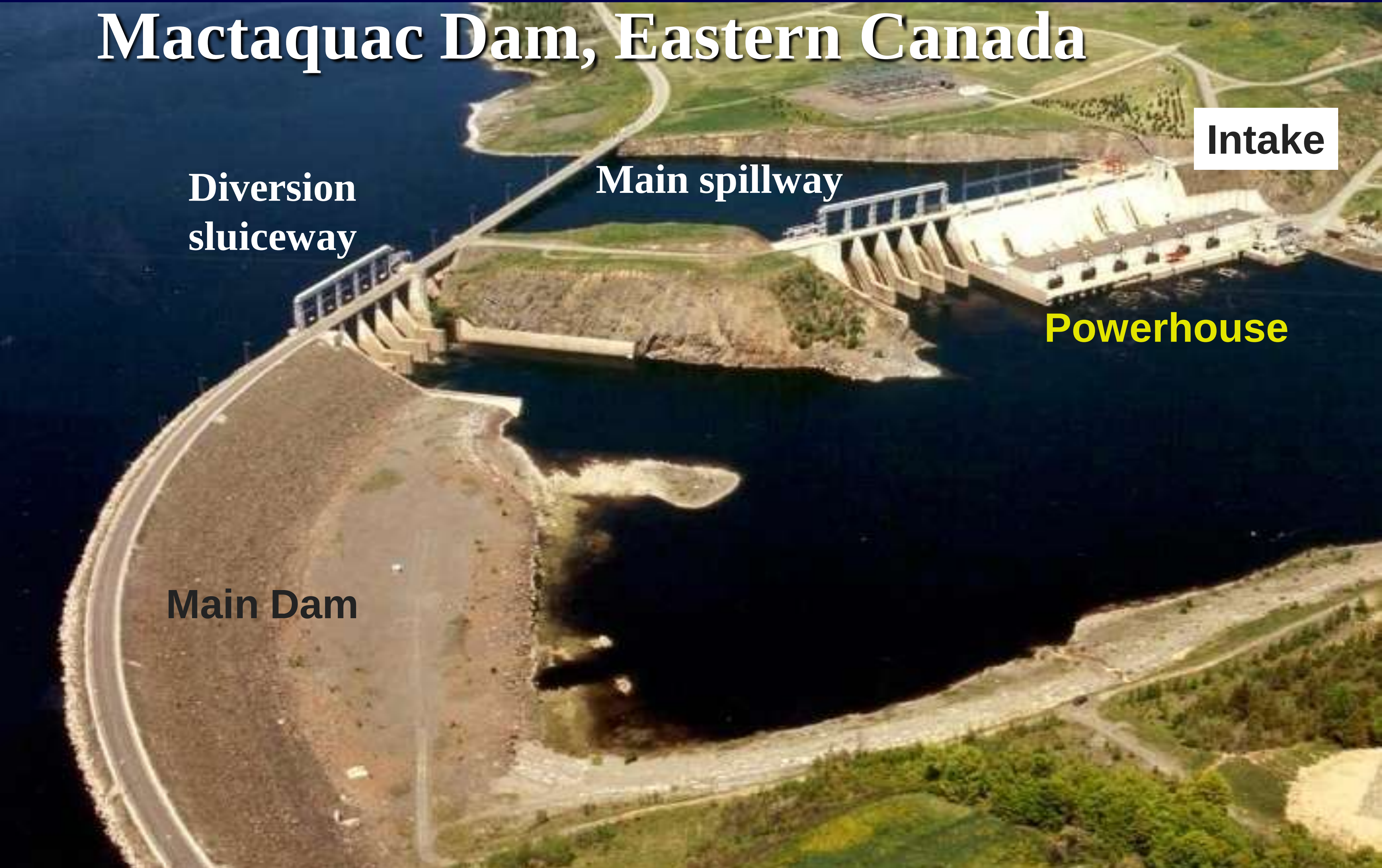
- **Strong measures should be applied to prevent AAR in new concrete constructions**
  - » **Testing of aggregate combinations**
  - » **Application of appropriate preventive measures**

- **Critical challenge for engineers → how to manage concrete structures affected by AAR !?**
  - » **Proper diagnosis of the source of the problem**
  - » **Establish prognosis → expansion to date and for future → select appropriate management action**

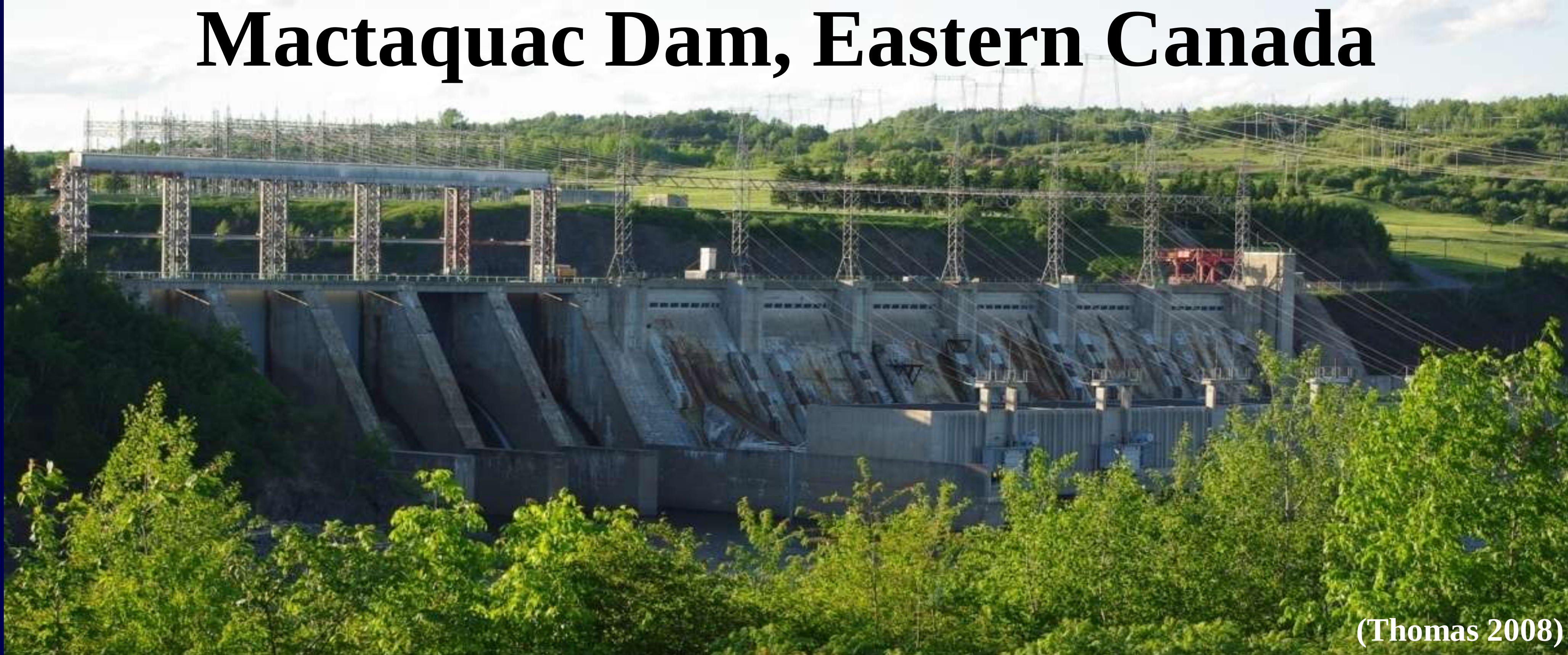
Thank you very much for your attention !!

Muito obrigado !!

Mactaquac Dam, Eastern Canada



Mactaquac Dam, Eastern Canada



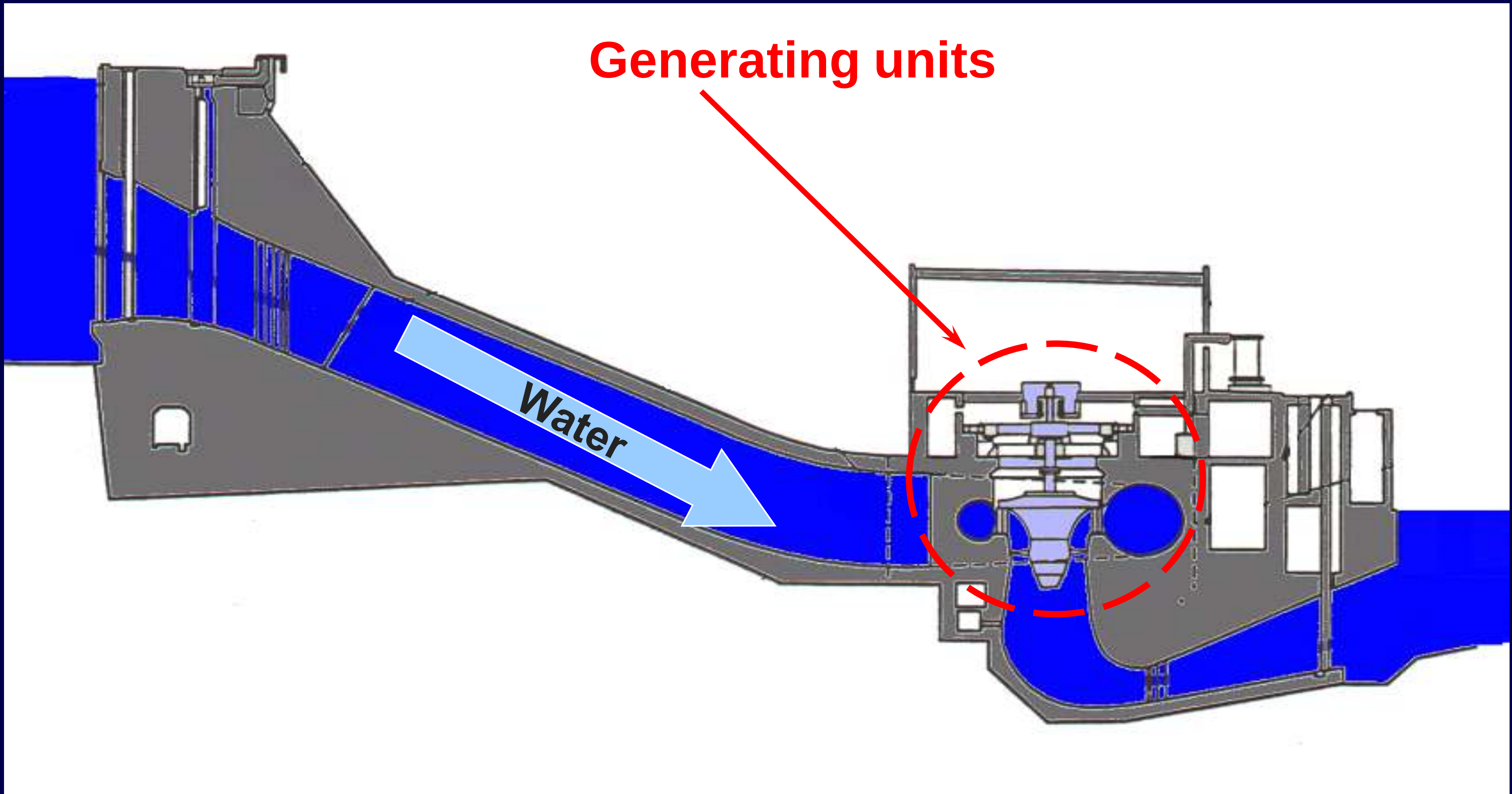
(Thomas 2008)

- <u>**Aggregate accepted for use based on ASTM C 227 !!!!**</u>
- **Vertical growing of the intake structure → ~ 18 cm**
- **Deformation rate → ~ 120 to 150 $\mu\varepsilon$/an**
- **Expenses for ASR-related repairs → ~ $6M / year <u>(> 75M$)</u>**
- **1 Billion $ to rebuild (2020)**

Intake structure

Mactaquac Dam, Eastern Canada

Mactaquac Dam, Eastern Canada



(Thomas 2008)

Stress relief

Temporary solution for structures where AAR has not ceased → recutting often required