Alkali-Aggregate Reactions in Concrete: Mechanisms, Testing, Mitigation, and USACE Experience

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Outline:

- Introduction to AAR
- Mechanisms
- Typical Damage
- Testing Methods
- Testing Guidance
- Mitigation Techniques
- Summary

Alkali-Aggregate Reactions

Alkali-Aggregate Reaction (AAR)
- Alkali-Carbonate Reaction (ACR)
- Alkali-Silica Reaction (ASR)

Alkali-Carbonate Reaction – ACR

… the reaction between the alkalis (sodium and potassium) in portland cement and certain carbonate rocks, particularly calcitic dolomite and dolomitic limestones, present in some aggregates; the products of the reaction may cause abnormal expansion and cracking of concrete in service.

Alkali-Silica Reaction – ASR *ACI 116*

… the reaction between the alkalis (sodium and potassium) in portland cement and certain siliceous rocks or minerals such as opaline chert, strained quartz, and acidic volcanic glass, present in some aggregates; the products of the reaction may cause abnormal expansion and cracking of concrete in service.

History of ASR

ASR affects all types of structures and has been implicated as a main or contributory cause of distress in thousands of concrete structures in North America.

- First discovered in the late 1930s
- In Monterey County and Los Angeles County
- Thomas Stanton of California State Division of Highways

Introduction to ASR

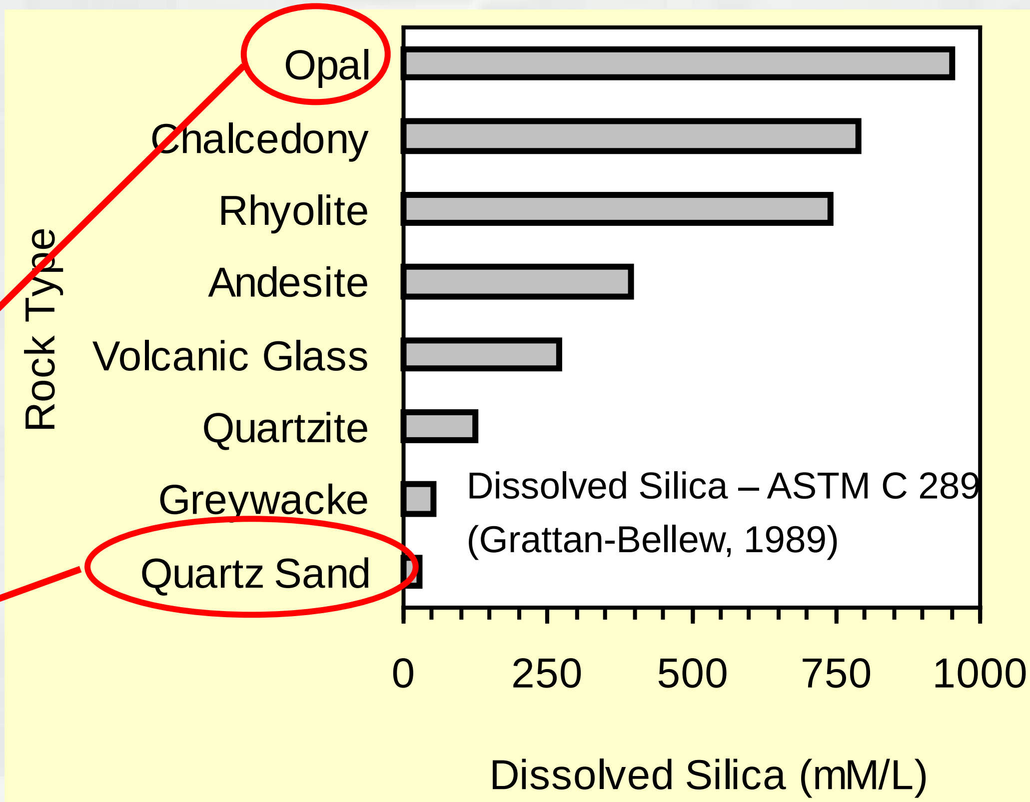
- What is the alkali-silica reaction (ASR)?
  - ASR occurs by the reaction of alkali hydroxyls (OH^-, Na^+, and K^+) present in the concrete pore solution with siliceous minerals found in some aggregates.
  - When hydrated, the ASR reaction product forms and expansive gel → cracking, spalling, and delamination

Alkali hydroxyl source + Reactive silica + H_2O ⟶

(ACI, 2009)

Rocks and Minerals

Amount of silica dissolved when a sample of crushed rock is immersed in 1M NaOH at 80ºC → depends on mineralolgy



Mineral		Chemical composition
Opal	→	SiO_2
Quartz		SiO_2

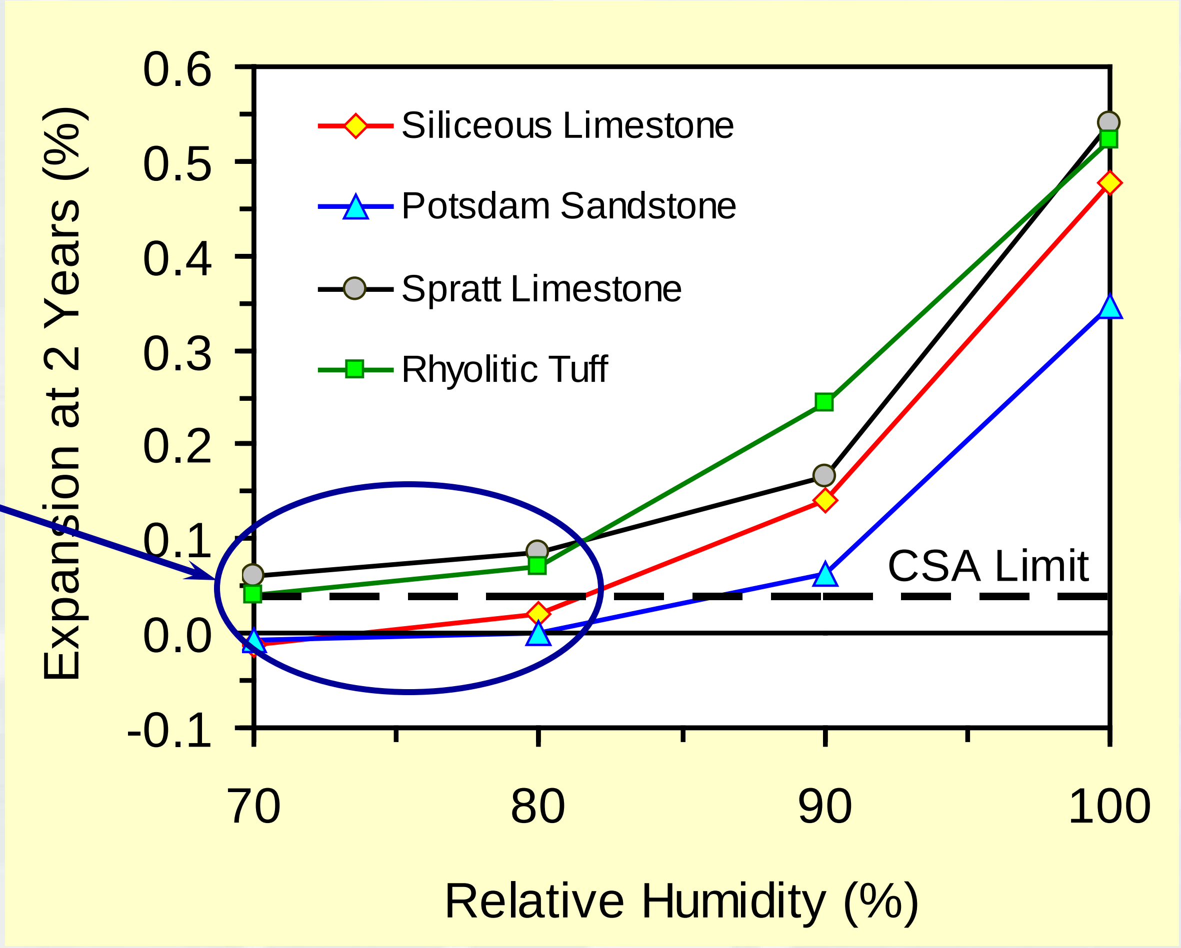
Not all siliceous minerals react to a significant degree in concrete.

Sources of Alkali in Concrete

- **Portland cement**
- Other cementing materials
  - Fly ash
  - Slag
  - Silica fume
- Chemical admixtures
- Wash water (if used)
- Aggregates
- External sources
  - Seawater
  - Deicing chemicals

Effect of Relative Humidity

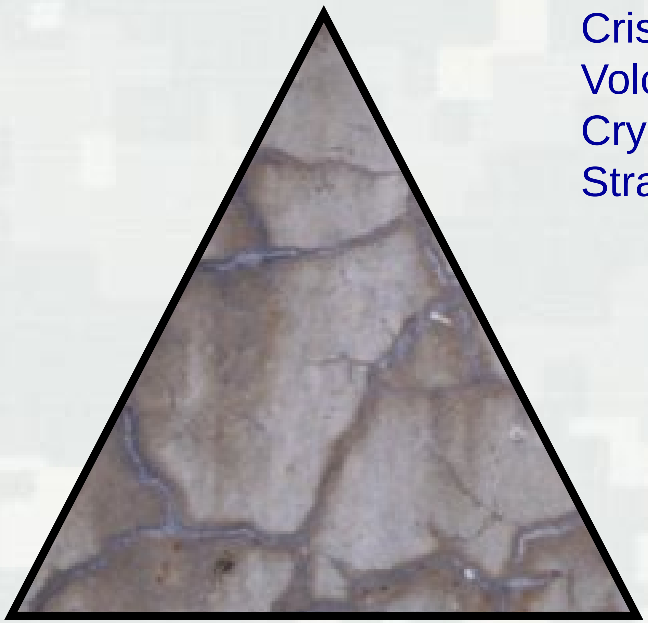
Little significant expansion if the relative humidity is maintained below about 80%



Requirements for ASR Damage

Reactive Minerals
- Opal
- Tridymite
- Cristobalite
- Volcanic glass
- Cryptocrystalline (or microcrystalline) quartz
- Strained quartz

Reactive Silica



Sufficient Alkali

Sufficient Moisture

From cement, deicing salts, SCMs

What does ASR do to structures?

- Damage by ASR in pavement and bridge structure:

Innovative solutions for a safer, better world

What does ASR do to structures?

- Corps of Engineers Civil Works structures:

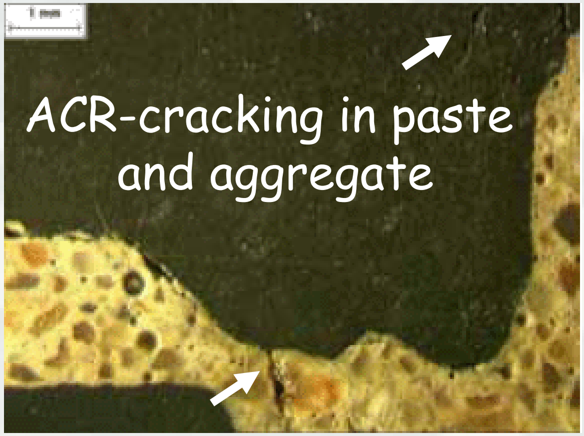
David Terry Lock and Dam

ASR in Lock and Dam 18

But what about ACR?

Alkali Carbonate Reaction

- First described in 1957 by Swenson in Kingston, Ontario, Canada
- Has since been identified in Virginia, Tennessee, Kentucky, Georgia... as well as in China, Spain, Austria…
- Generally, lithological characteristics typical in ACR-reactive aggregates include:
  - calcite ($CaCO_3$)-to-dolomite ($CaMg(CO_3)_2$) ratio of ~1:1*
  - clay content (or insoluble residue) of 5-25% by mass
- The dolomite crystals in the aggregate are chemically altered by the alkali solutions in a multistep process leading to expansion.



source: http://www.fhwa.dot.gov/pavement/pccp/pubs/04150/chapt10.cfm

ACR (along with ASR) in Corps Structures

Chickamauga Lock and Dam

ACR at Tinker Air Force Base

- Reaction rims and microfracturing of coarse aggregates.
- Approx. 1:1 calcite-to-dolomite ratio by XRD.

What are the ramifications?

1) Expansion, misalignment and binding of mechanical systems, failure of joints

2) Potential to induce stresses if the concrete is confined

3) Reductions in strength and stiffness due to micro- and macro-cracking

How do I test for AAR?

Current Test Methods for ASR

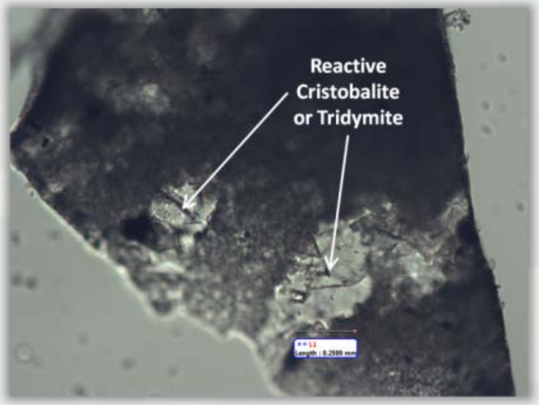
- ***ASTM C 295 - Standard Guide for Petrographic Examination of Aggregates for Concrete***
- ASTM C 289 - Standard Test Method for Potential Alkali-Silica Reactivity of Aggregates (Chemical Method)
- ASTM C 227 - Standard Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations
- ***ASTM C 1260 - Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)***
- ***ASTM C 1567 – like C1260 but for mitigation***
- ***ASTM C 1293 - Standard Test Method for Concrete Aggregates by Determination of Length Change of Concrete Due to Alkali-Silica Reaction***

Does the mineralogy of my aggregate make it reactive?

- Petrographic analysis (ASTM C295):
  - ► Identify reactive components of aggregates based on recommendations in EM 1110-2-2000.
    - Presence of any opal.
    - >5% of particles of chert in which any chal-cedony is detected.
    - >3% of particles of glassy igneous rocks in which any acid or intermediate glass is detected.
    - >1% of particles of tridymite or cristobalite detected.
    - >20% of particles of strained quartz in an aggregate in which the measured average extinction angle is at least 15 degrees.
    - >15% of particles of graywacke, argillite, phyllite, or siltstone containing any very finely divided quartz or chalcedony.

Petrographic Analysis

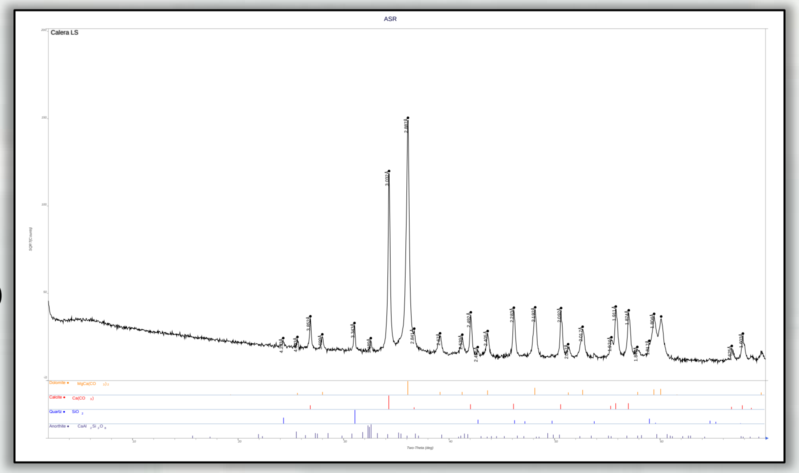
- ASTM C295: assessed potential reactivity of aggregates studied based on mineralogy.
  - Visual examination.
  - Quantitative x-ray diffraction (XRD) to identify reactive minerals present in aggregates.
  - Refractive index testing using petrographic microscopy to identify highly-reactive amorphous phases present in aggregates.



Petrographic Analysis

- Comparison between a non-reactive limestone (130040) and a highly reactive opal (130039)

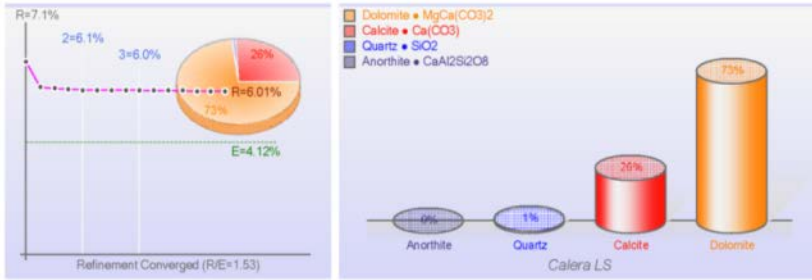
Non-Reactive
Ag. 130040



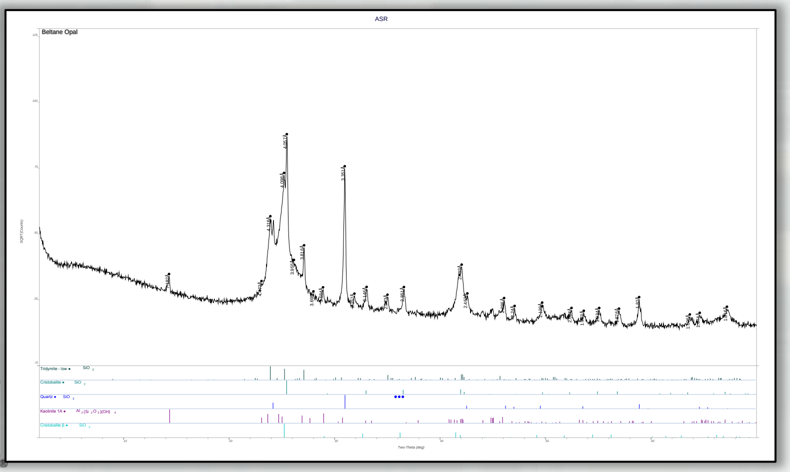
Phase ID (4)	Chemical Formula	PDF-#	NA	NR	NP	Wt% (esd)	RIR
Calcite	$Ca(CO_3)$	01-083-0578	---	12	14	26 (0)	3.21
Quartz	SiO_2	98-000-0369	2	34	7	1 (0)	4.29
Anorthite, ordered	$CaAl_2Si_2O_8$	00-041-1486	---	58	7	0 (0)	0.41
Dolomite	$MgCa(CO_3)_2$	01-083-1766	---	15	14	73 (1)	2.53

XRF(Wt%): CaO=36.7%, SiO2=1.0%, Al2O3=0.1%, MgO=16.0%, CO2=46.3%

Refinement Converged (R/E=1.53), Round=3, Iter=5, P=43, R=6.3% (E=4.12%, EPS=0.5)



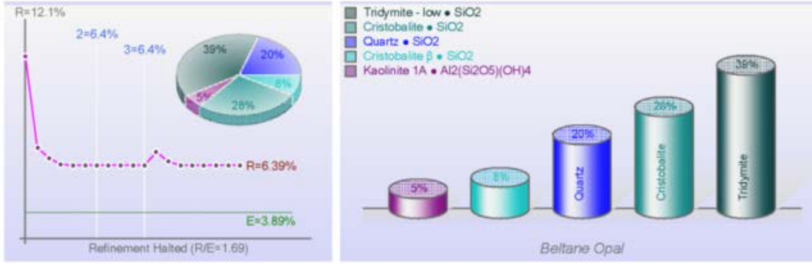
Reactive
Ag. 130039



Phase ID (5)	Chemical Formula	PDF-#	NA	NR	NP	Wt% (esd)	RIR
Quartz	SiO_2	01-074-1811	---	12	14	20 (1)	3.06
Tridymite - low	SiO_2	01-088-1535	---	140	16	39 (2)	1.59
Kaolinite 1A	$Al_2(Si_2O_5)(OH)_4$	01-078-1996	---	77	13	5 (1)	1.12
Cristobalite, α, syn	SiO_2	01-089-3434	---	23	14	28 (1)	4.90
Cristobalite β, syn	SiO_2	01-082-1405	---	23	14	8 (1)	4.77

XRF(Wt%): SiO2=97.1%, Al2O3=2.1%

Refinement Halted (R/E=1.69), Round=3, Iter=7, P=64, R=6.58% (E=3.89%, EPS=0.5)

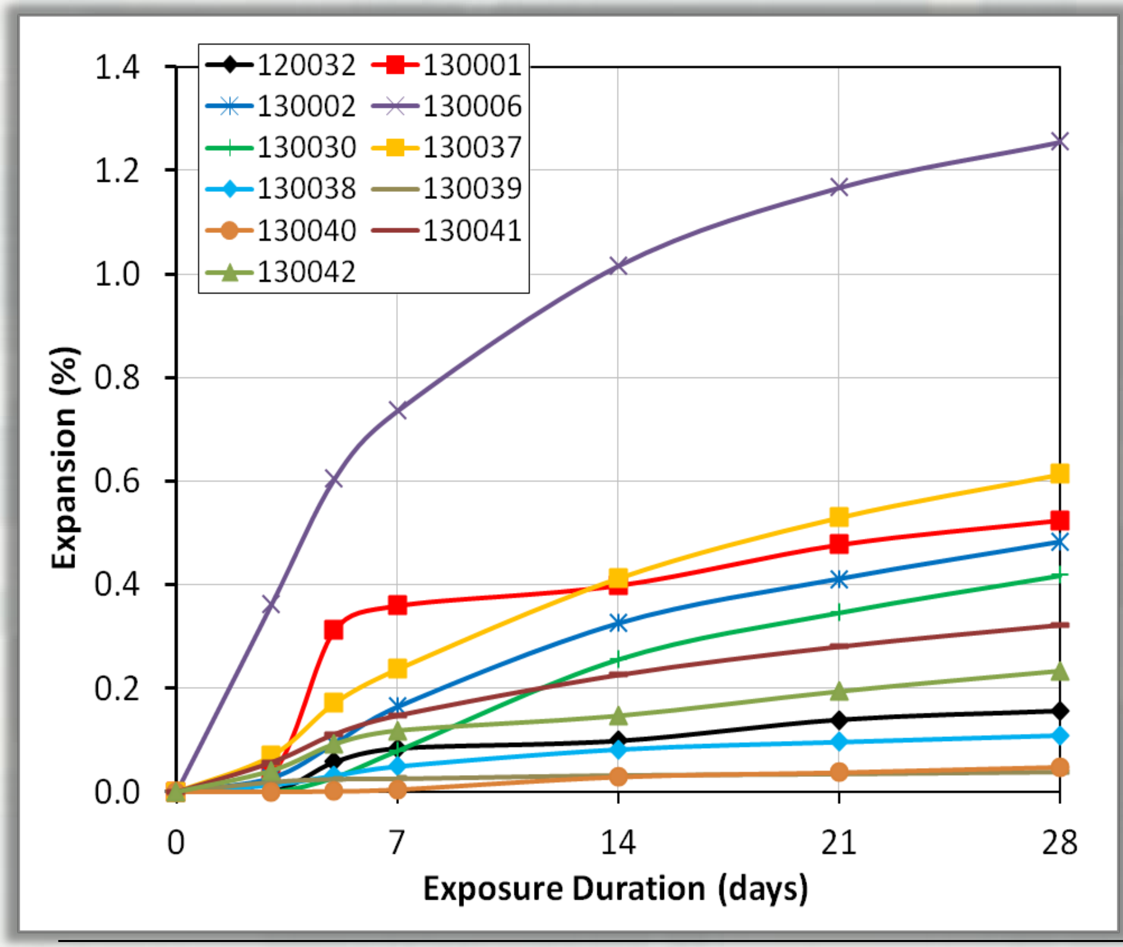


Measure Expansion by ASR

- Accelerated mortar bar test (AMBT, ASTM C1260)
  - Mortar made to test aggregate reactivity
  - Can evaluate fine aggregate and crush coarse aggregates for testing
  - Stored in 1N NaOH solution at 80°C
  - Expansion measured for 14 days
  - Interpretation of results:
    - > 0.2% = reactive
    - 0.1% to 0.2% = potentially reactive
    - < 0.1% = considered innocuous
  - Primary test method in UFGS and DOT specifications

ASTM C1260 Expansion

- Results from ASTM C1260 showing a wide range of reactivity in natural aggregates:



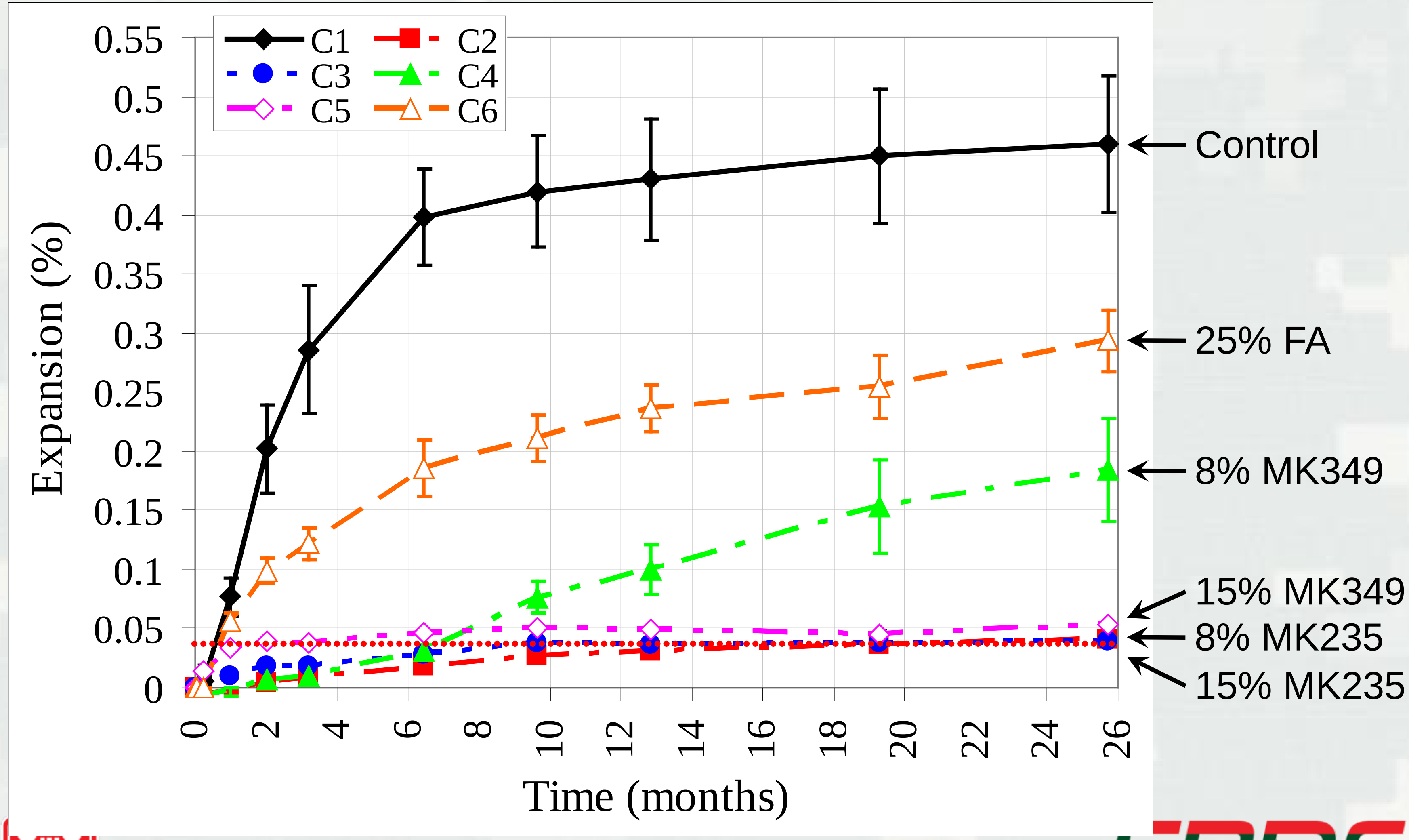
Additional Test Methods

- AMBT for evaluating mitigation (ASTM C1567)
  - Similar procedures as ASTM C1260
  - Additional guidance provided for evaluating ASR mitigation with supplementary cementitious materials
- Concrete prism test (CPT, ASTM C1293)
  - Test performed on 3x3x11.25” concrete prisms
  - Can evaluate coarse and fine aggregates
  - One - two year duration due to 38C temperature
  - Can evaluate mitigation options with SCMs
  - Considered to be best predictor of field performance

Concrete Prism Test ASTM C1293

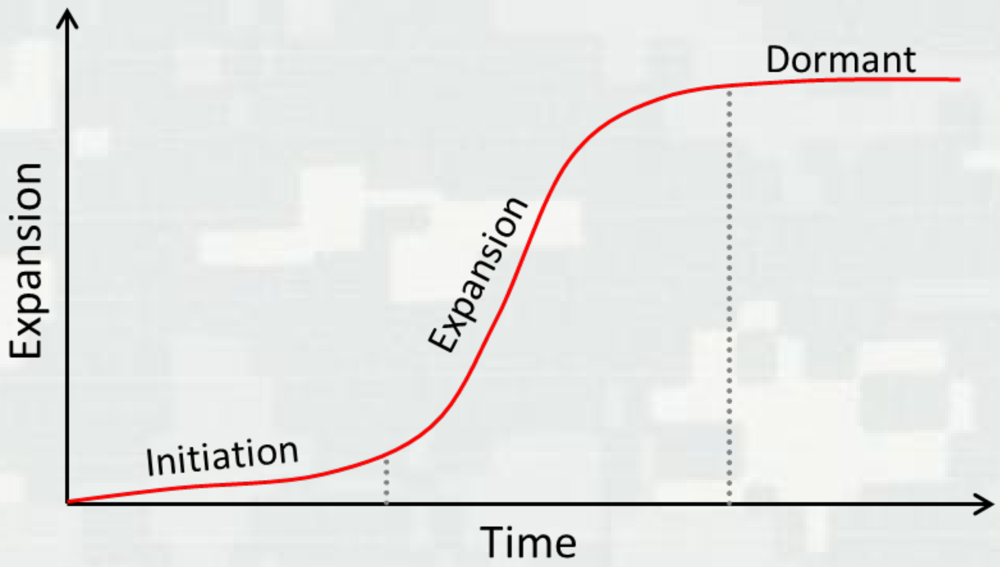
- CPT expansion test
  - Concrete prisms made to evaluate aggregate reactivity
  - Alkali loading increased by adding NaOH to mix water
  - Store at 100% RH and 38^{o}C
  - Expansion measure for 1 to 2 years
    - 2 years for mixes with SCMs
  - Interpretation of expansion results:
    - > 0.04% = potentially reactive
    - < 0.04% = considered innocuous
  - Better predictor of field performance

Concrete Prism Test Results



Residual Expansion in Existing Structures

- Test cores using ASTM C1260 exposure
  - ▸ Worse-case-scenario of expansion with infinite alkalis
- Test cores using ASTM C1293 exposure
  - ▸ More realistic expansion using only internal alkalis
  - ▸ Just takes a lot longer…



Where is my structure in the expansion process vs. time?

Conduct a residual expansion test!

Many other non-standard methods out there…

Some Common ACR Test Methods

- ASTM C 295 - Standard Guide for Petrographic Examination of Aggregates for Concrete
- ASTM C 586 – Test Method for Potential Alkali Reactivity of Carbonate Rocks for Concrete Aggregates (Rock Cylinder Method)

Aggregate Tests

- ASTM C 1105 – Length Change of Concrete Due to Alkali-Carbonate Rock Reaction
- ASTM C 1293 - Standard Test Method for Concrete Aggregates by Determination of Length Change of Concrete Due to Alkali-Silica Reaction

Concrete Tests

Recommended Tests

DoD Guidance per UFGS

“Fine and coarse aggregates must show expansions less than 0.08 percent at 16 days after casting when testing in accordance with ASTM C1260. Should the test data indicate an expansion of 0.08 percent or greater, reject the aggregate(s) or perform additional testing using ASTM C1567 using the Contractor's proposed mix design.”

AND

“Aggregates must not possess properties or constituents that are known to have specific unfavorable effects in concrete when tested in accordance with ASTM C295/C295M.”

- From: UFGS Division 03 Section 03 30 00: Cast-In-Place Concrete

How can AAR be mitigated?

How to prevent ASR damage in new construction

Alkalis + Reactive Silica + Moisture ⇨ ASR Gel

Avoid reactive aggregate

- Accelerated testing
- Selective quarrying
- Known sources

How to prevent ASR damage in new construction

Alkalis + Reactive Silica + Moisture ⇨ ASR Gel

Avoid high alkali content

- Use low alkali portland cement: $Na_2 0_e < 0.60$
- ensure alkali content in concrete is low: levels < 3kg/m³ or 5lb/yd³ are recommended
- Use low alkali supplementary cementing materials in appropriate dosages

  - 10-15% metakaolin
  - 25% or more Class F fly ash
  - 25-40% or more slag
  - 10% or more silica fume
  - silica fume in a ternary blend with Class C or F fly ash or slag

How to prevent ASR damage in new construction

Alkalis + Reactive Silica + Moisture ⇨ ASR Gel

Limit the availability of moisture:

- Design
- Mix proportioning, materials selection, and construction
  - use low w/c
  - specify SCM's
  - maintain good curing practices

Often, a combination of preventative measures is the best approach

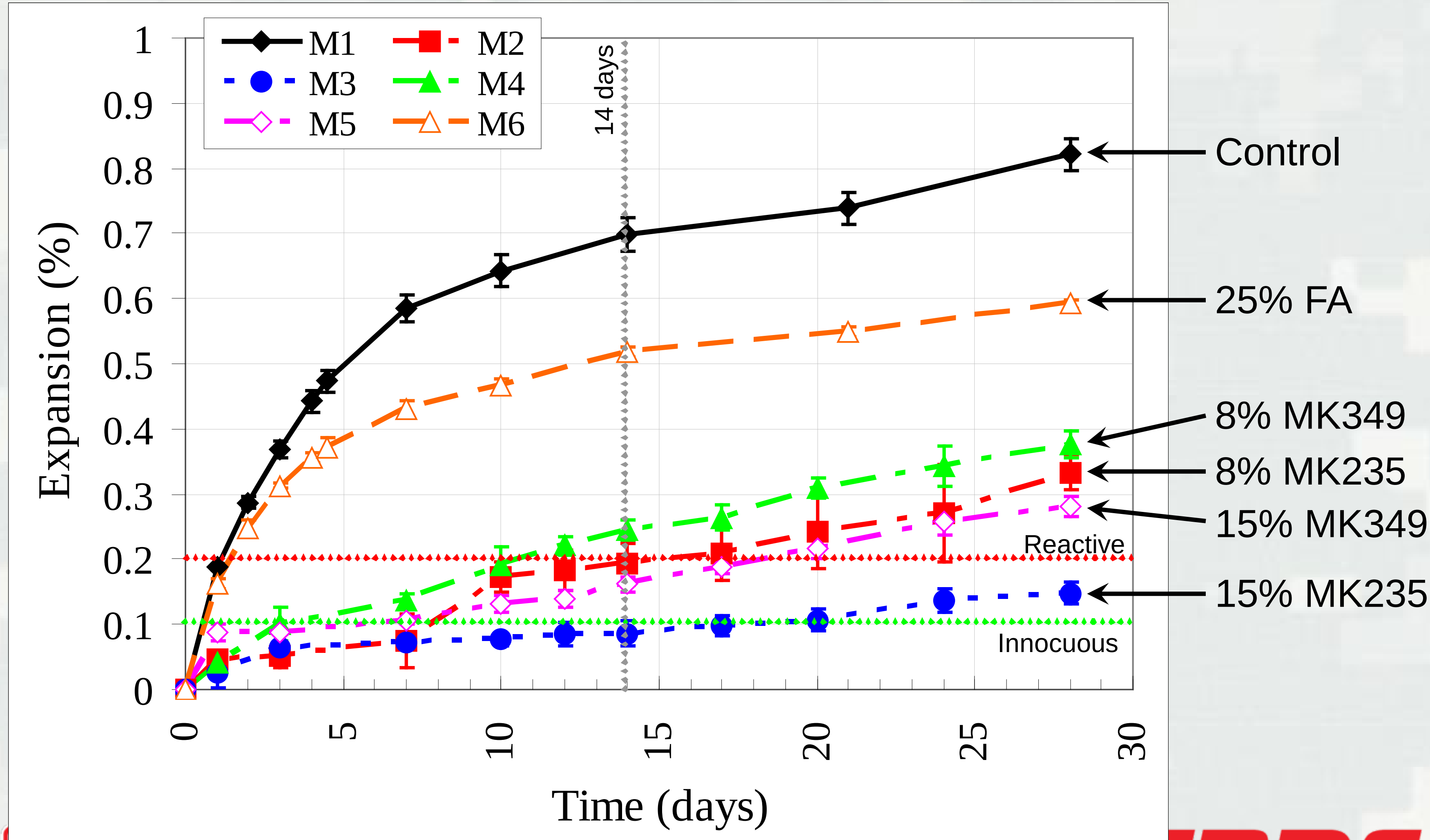
ASR mitigation using SCMs

- The use of supplementary cementitious materials (SCMs) is a common effective ASR mitigation strategy.
  - ► Common SCMs: Class C and Class F Fly Ash, Silica Fume, Metakaolin, Slag…
- How do SCMs reduce ASR:
  - ► Pozzolanic reactions consume CH and result in densification of the paste, reducing permeability.

$$\text{SCM} + \text{CH} + \text{Water} \rightarrow \text{C-S-H}$$

  - ► Formation of supplementary C-S-H by pozzolanic reactions provides additional sites for alkali binding.

AMBT results: Binary blends



Mitigation of ACR: Challenging

- Avoid reactive aggregate
- Because ACR effectively regenerates alkalis, use of low-alkali cement (even with Na_2O_e<0.40%) or SCMs are often ineffective in reducing ACR to acceptable limits.

$$CaMg(CO_3)_2 + 2\ NaOH \rightarrow Mg(OH)_2 + CaCO_3 + Na_2CO_3$$

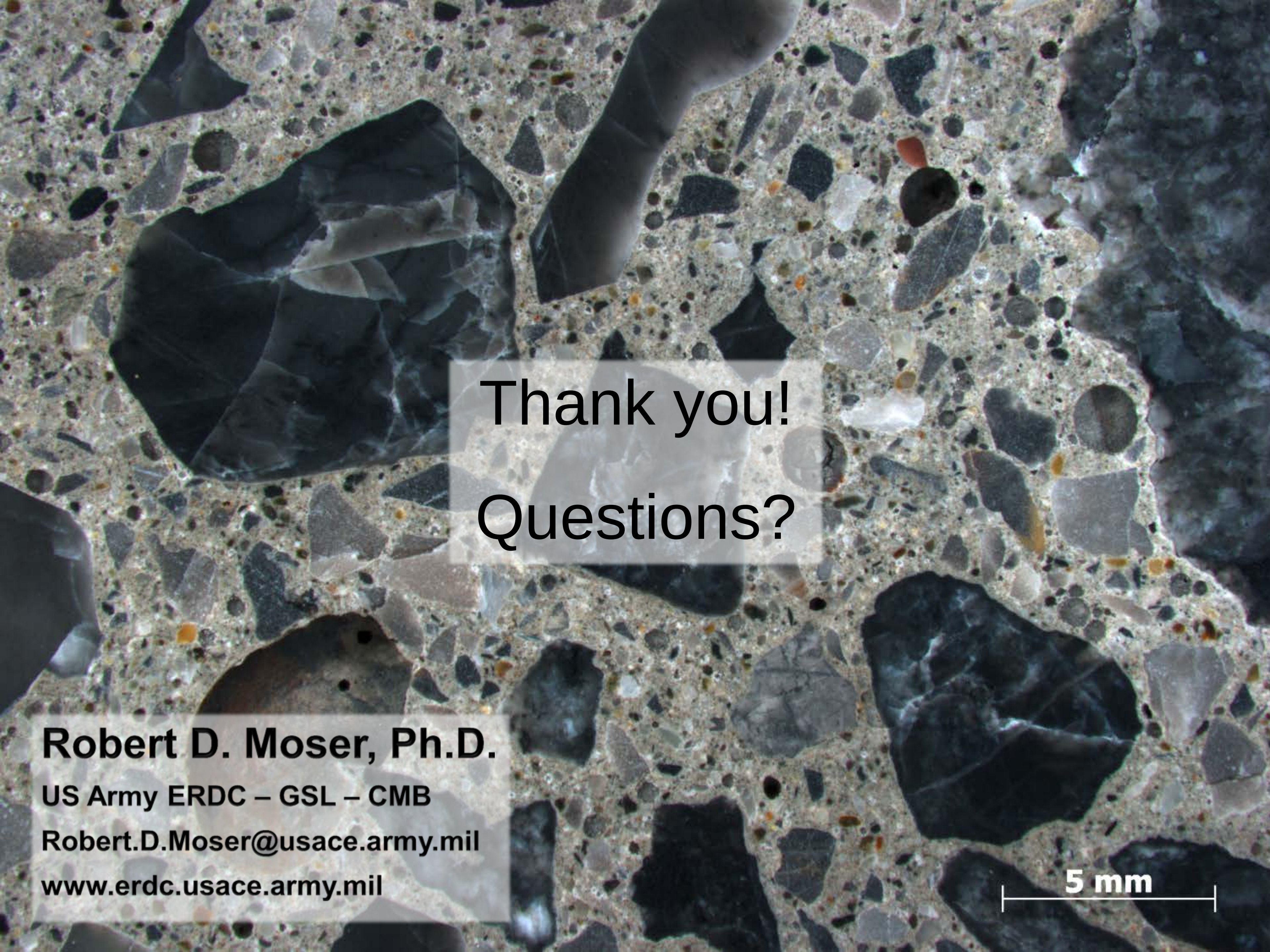
$$Ca(OH)_2 + Na_2CO_3 \rightarrow 2NaOH + CaCO_3$$

- Reducing the aggregate MSA shown to reduce ACR
- Selective quarrying of non-reactive aggregate
- Blending no more than 20% reactive aggregate (either coarse or fine) with non-reactive aggregate or blending up to 15/85% when both reactive fine and coarse aggregates are to be used.

Just to summarize…

Summary

- AAR (including ASR and ACR) are an important consideration for concrete durability.
- Reactive aggregates, moisture, and alkalis are required for both ASR and ACR.
- ASR occurs much more frequently that ACR.
- Many test methods available to identify aggregate reactivity and effectiveness of mitigation.
- ASR can be mitigated by reducing permeability, use of SCMs, and other means.
- ACR very difficult to mitigate…



Thank you!

Questions?

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