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# Aggregates & ASR – Types, Properties, and Testing

Presented by

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Materials Science & Engineering

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## Abstract

The physical and chemical properties of aggregates play an important role in determining their suitability for use in portland cement concrete (PCC). Mechanical strength, coefficient of thermal expansion, possible chemical reactivity, and soundness are a few aggregate properties that significantly affect the long-term performance and durability of portland cement concrete. This presentation will cover the mineralogical characteristics of different aggregates as well as discuss known deleterious issues. Alkali-Silica Reaction (ASR) and Alkali-Aggregate Reaction (AAR) mechanisms, contributing factors, and mitigation will also be covered.

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## Abstract

The **physical and chemical properties** of aggregates play an important role in determining their suitability for use in portland cement concrete (PCC). **Mechanical strength, coefficient of thermal expansion, possible chemical reactivity**, and soundness are a few aggregate properties that significantly affect the long-term performance and durability of portland cement concrete. This presentation will cover the mineralogical characteristics of different aggregates as well as discuss known deleterious issues. **Alkali-Silica Reaction (ASR)** and Alkali-Aggregate Reaction (AAR) mechanisms, contributing factors, and mitigation will also be covered.

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## Introduction

- Aggregates typically occupy 70 to 80 percent of concrete by volume
- Most often derived from natural rock (crushed stone or gravel) but can also be obtained from industrial byproducts (slag) or produced to create lightweight or heavyweight concrete
- For most normal-weight concrete, the strength of the concrete is independent of aggregate type
  - High strength concrete being the exception

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## Introduction

- Aggregates should be hard and strong, free of undesirable impurities, and chemically stable
- Soft, porous rocks can limit strength and wear resistance, may break down during mixing, and may produce fines
- Aggregates should be free of silt, clay, dirt, or organic manner

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## Introduction

- The mineralogical and chemical properties of the aggregates affect their performance in concrete
- We will examine key properties and associate those with aggregate mineralogical and chemical properties
  - Strength & Other Physical Properties
  - CTE
  - Freeze-Thaw Durability
  - Alkali Reactivity

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## Strength and Other Physical Properties

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## Geology 101

| Igneous | | Sedimentary | | Metamorphic |
|---|---|---|---|---|
| Formed from molten rock | | Formed by particle deposition or chemical precipitation | | Formed by heat/pressure acting on existing rock |
| *Extrusive* | *Intrusive* | *Calcareous* | *Siliceous* | |
| Felsite<br>Rhyolite<br>Andesite<br>Basalt<br>Obsidian<br>Pumice | Granite<br>Syenite<br>Granodiorite<br>Diorite<br>Gabbro<br>Diabase | Limestone<br>Dolomite | Sandstone<br>Shale<br>Chert | Slate<br>Schist<br>Gneiss<br>Quartzite<br>Marble |

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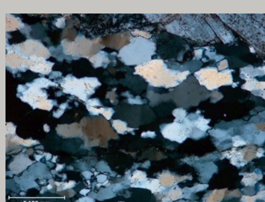
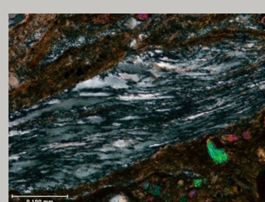
## Grain Structure

**Quartz**



**Strained Quartz**



http://earth.usc.edu/~behr/wbehr/Research/Entries/2008/10/21_EPISTEMIC_UNCERTAINTY_IN_FAULT_SLIP_RATES.html

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## Strength

- Rock type
- Loading
- Processing

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## Strength

- Strength of an aggregate material can be inferred from compressive or tensile tests on rock samples
  - Most exceed 10,000 psi compressive (Meininger, STP 169D)
- Performance in concrete varies due to confinement and loading
- Cracks/fissures resulting from crushing results in lower strengths

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## Strength

- Paste bond for load transfer is critical to strength
  - paste-coating bond > coating-aggregate bond (bad)
- WisDOT research on clay coatings (Munoz, 2007)
  - May hinder or accelerate the hydration process
    - Imbibe water or contribute cations
  - Can stiffen paste and reduce bond with aggregate
  - Can increase drying shrinkage
  - Negatively impact air entrainment
    - Water absorption and AEA adsorption

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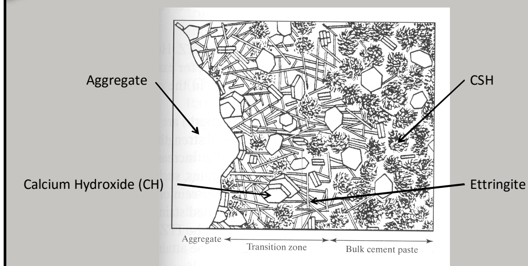
## Interfacial Transition Zone




Mindess, Young & Darwin

## Interfacial Transition Zone

- Weak zone between the aggregate and bulk paste
- Has a major impact on strength and permeability
- The interfacial zone is 10 to 50 mm in thickness
  - Locally high *w/c*
  - "wall effect" (packing problems)
  - calcium hydroxide and ettringite are oriented perpendicular to aggregate surface
  - Greater porosity and few unhydrated cement grains
- Microcracking commonly exists in transition zone
- Results in shear-bond failure and interconnected macroporosity, which influences permeability
- Modification of transition zone is key to improving concrete

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## Strength

- Other obvious factors
  - Absorption
    - More than just mix design…
  - Texture
    - Mineralogy – tendency to polish
    - Gravel vs. Quarried
  - Shape
    - Workability
    - Strength
    - Other?

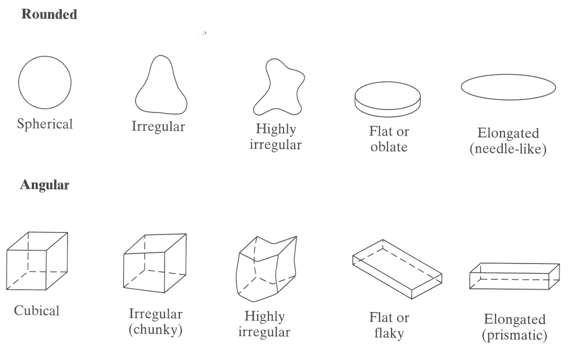


FIGURE 7.1
Classification of aggregate shapes.
From (BS) 812: Part 1, 1975

**Mindess, Young & Darwin**

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## Shape

- Particle shape impacts concrete durability
  - Mortar Flaking
    - Most commonly associated with F-T cycling
    - Results from a combination of:
      - Inadequate curing
      - Thin layers of paste above aggregate irregular shape particles
  - Flat & Elongated (water voids)
    - Bleed water gets trapped below flat & elongated aggregates
    - Forms water void
    - Subsequent freezing of water in the void leads to expansion

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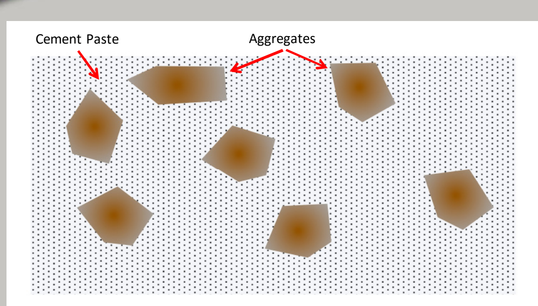

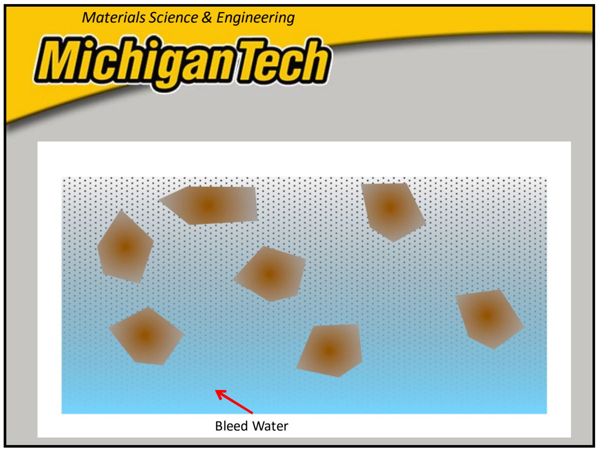
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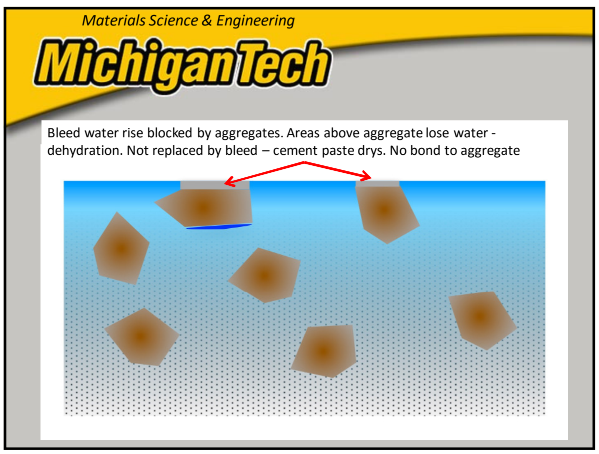
Bleed Water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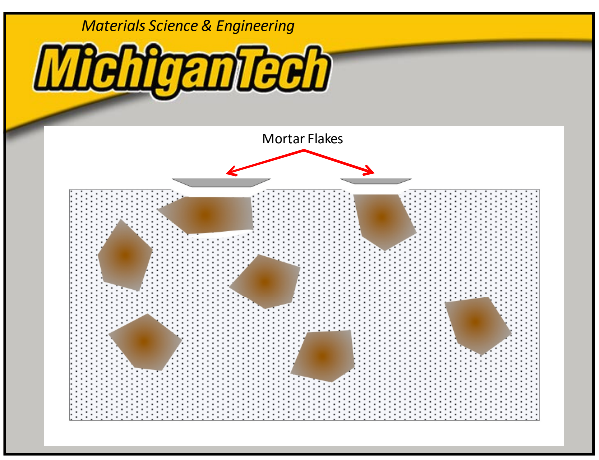
Bleed water rise blocked by aggregates. Areas above aggregate lose water - dehydration. Not replaced by bleed – cement paste drys. No bond to aggregate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Mortar Flakes

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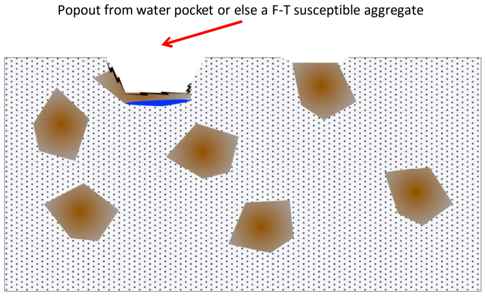
Popout from water pocket or else a F-T susceptible aggregate



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## Mortar Flaking Prevention

- Proper air entrainment
- *w/c* < 0.45

(Proper air entrainment and w/c < 0.45: Standard fare whenever F-T is a factor)

- Do not over finish
- Do not finish when bleed water present/rising
- Susceptible to scaling forces – avoid late season placements and salt use at early ages
- Sealers

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## Coefficient of Thermal Expansion

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## Coefficient of Thermal Expansion

- The measure of how concrete changes in volume in response to temperature change
  - Change in unit length per degree of temperature change
- Largely determined by coarse aggregate and the degree of saturation of the aggregate
- Considered critical to pavement design using MEPDG
- Test method – AASHTO T 336-11

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FHWA-HIF-09-015

Table 1. Coefficient of Thermal Expansion (CTE) of Concrete by Aggregate Type (LTPP Standard Date Release 25.0)

| Primary Aggregate Class | Average CTE (/°F x $10^{-6}$) | Standard Deviation (s) (/°F x $10^{-6}$) | Average CTE (/°C x $10^{-6}$) | Standard Deviation (s) (/°C x $10^{-6}$) | Sample Count[1] |
|---|---|---|---|---|---|
| Andesite | 4.32 | 0.42 | 7.78 | 0.75 | 52 |
| Basalt | 4.33 | 0.43 | 7.80 | 0.77 | 141 |
| Chert | 6.01 | 0.42 | 10.83 | 0.75 | 106 |
| Diabase | 4.64 | 0.52 | 8.35 | 0.94 | 91 |
| Dolomite | 4.95 | 0.40 | 8.92 | 0.73 | 433 |
| Gabbro | 4.44 | 0.42 | 8.00 | 0.75 | 8 |
| Gneiss | 4.87 | 0.08 | 8.77 | 0.15 | 3 |
| Granite | 4.72 | 0.40 | 8.50 | 0.71 | 331 |
| Limestone | 4.34 | 0.52 | 7.80 | 0.94 | 813 |
| Quartzite | 5.19 | 0.50 | 9.34 | 0.90 | 131 |
| Rhyolite | 3.84 | 0.82 | 6.91 | 1.47 | 7 |
| Sandstone | 5.32 | 0.52 | 9.58 | 0.94 | 84 |
| Schist | 4.43 | 0.39 | 7.98 | 0.70 | 30 |
| Siltstone | 5.02 | 0.31 | 9.03 | 0.56 | 21 |
| | | | | Total Sample Count | 2,251 |

1. A total of 2,991 CTE values are available in LTPP Standard Data Release 25.0 (January 2011); 628 CTE values were not used due to aggregate class not defined or only one sample available for the primary aggregate type, and 112 CTE outlier values were also not included in the table.

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## Aggregate F-T

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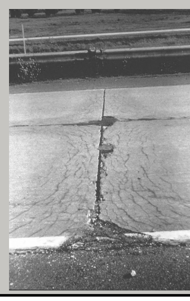
## Aggregate F-T (D Cracking)

- Freezing and thawing of susceptible, coarse aggregate particles
  - Two mechanisms
    - Fracture as they freeze - then dilate resulting in cracking of the surrounding mortar
    - Allow rapid expulsion of water during freezing - dissolution of soluble paste components in paste
- Key aggregate properties
  - Aggregate size
  - Pore size distribution
  - Aggregate strength



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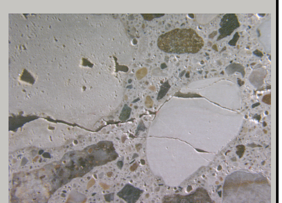
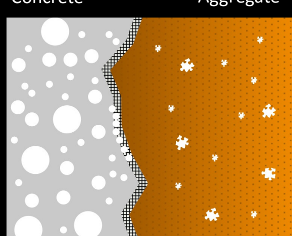
## Aggregate F-T (D Cracking)

- Most D-cracking susceptible aggregates are of sedimentary origin (e.g., cherts, sandstones, shales, limestones)
- Can be calcareous or siliceous, and can be gravel or crushed rock



## Aggregate F-T Mechanisms



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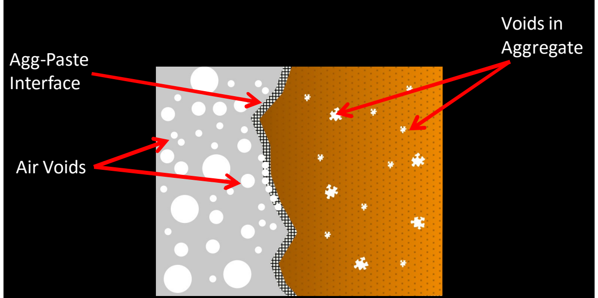
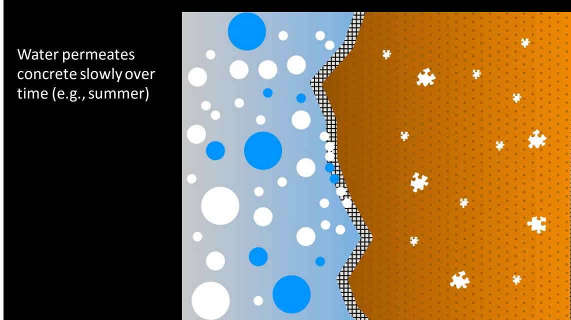



## Aggregate F-T Mechanisms

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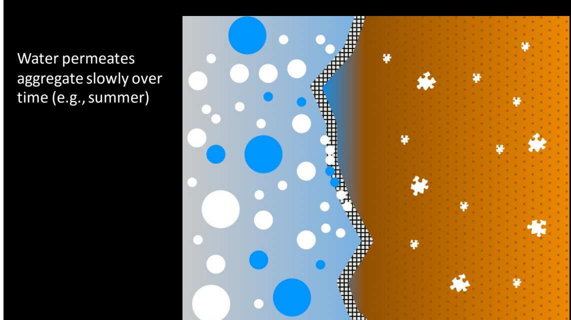
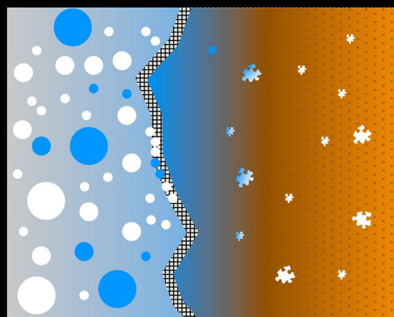


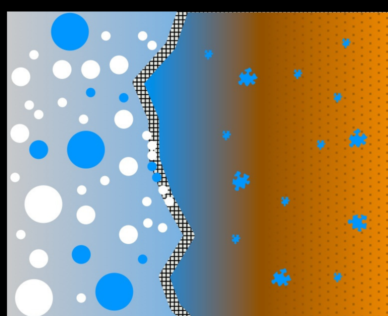
## Aggregate F-T Mechanisms

Water fills voids in aggregate



## Aggregate F-T Mechanisms

Water continues to permeate filling voids at depth in the aggregate

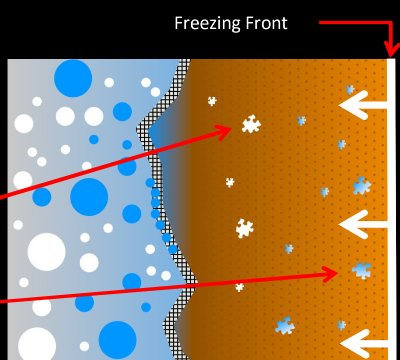


Freezing front forms ice, forcing liquid water out of the aggregate

**Occurs <u>QUICKLY</u> !!!**

Water in voids near aggregate edge can escape

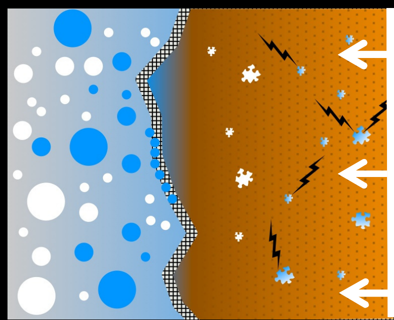
**<u>Water at depth CANNOT</u>**



## Aggregate F-T Mechanisms

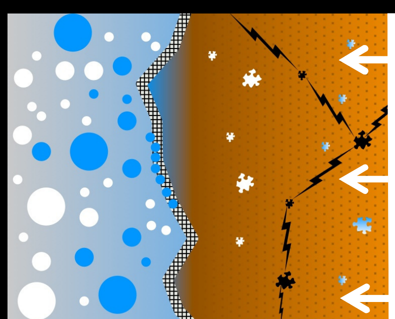
As water is forced out hydraulic pressures develop

If those pressures exceed the tensile strength of the aggregate cracks form



## Aggregate F-T Mechanisms

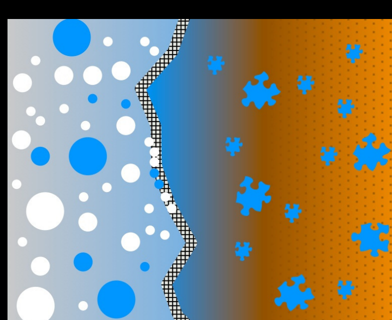
Continued pressure propagates cracks and causes aggregate dilation



## Aggregate F-T Mechanisms

**Alternate Mechanism**

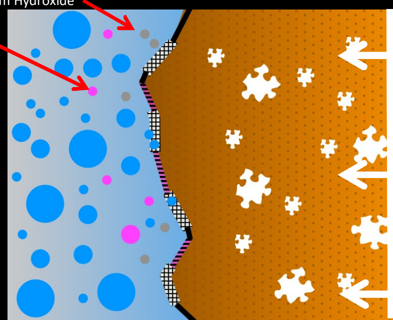
Larger voids, larger volume of water absorbed by aggregate



## Aggregate F-T Mechanisms

Ettringite

Calcium Hydroxide



**Alternate Mechanism**

Water is pushed out quickly and causes dissolution of phases at the aggregate-paste interface

Lose bond, socketing

Material re-deposits in air voids

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## Aggregate F-T

- Powers' hydraulic pressure theory is generally considered to provide a reasonable description of the actions taking place inside aggregate particles during freezing
- In a critically saturated aggregate, excessive pressures can develop due to the volume increase associated with ice formation

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## Aggregate F-T

- The expansion associated with ice formation may be accommodated by either elastic deformation and / or the expulsion of unfrozen water
  - The tensile capacity of an aggregate can be exceeded when the expansion due to ice formation cannot be accommodated by elastic deformation
- In other cases, the expulsion of water from sound aggregate particles during a freezing event can result in damage to the surrounding paste phase

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## Aggregate F-T

- The hydraulic pressures are greater when the flow is through smaller sized pores and along longer flow paths
  - Smaller top size – shorter path for flow
- It is fairly well established that the aggregate pore system is the most important factor contributing to its F-T durability

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## F-T Durable Aggregate Properties

- Two related elements of the pore system that are of particular interest are the **porosity and pore size distribution**
  - **Porosity** is a characteristic that is easy to determine and provides a measure of the total volume of water contained within a fully saturated aggregate
  - **Pore size** is a measure of the physical dimensions of the various elements of the accessible pore volume

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## F-T Durable Aggregate Properties

- Pore size is more difficult to determine, but important
  - Indication of an aggregate's potential to become critically saturated
  - Measure of its permeability or resistance to fluid flow during a freezing event
  - Perhaps the single most significant pore characteristic is the volume of the total porosity contained within a specific range of pore sizes that have been empirically related to aggregate F-T durability

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## F-T Durable Aggregate Properties

- The exact limit of detrimental pore sizes is not definitively established, but has been **reported to be in the range of under 0.10 to 5 micron**
- Pores smaller are not considered detrimental for one of two reasons
  - Their size is such that the water in them will not freeze at normal winter temperatures
  - Volume of water is small enough that it does not contribute significantly to stresses in either the aggregate or the surrounding paste

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## F-T Durable Aggregate Properties

- Larger pores are not considered detrimental to the aggregate
  - They do not become critically saturated
  - Their permeability is high enough that they do not generate excessive hydraulic pressures
- As with air voids, deicer salts can change the level of saturation within the aggregate

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## **Alkali-Silica Reaction**

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## Stanton's Bridge (ca. 1930)

Alkali-Aggregate Reactivity (AAR) Facts Book. Thomas, M.D.A., Fournier, B., Folliard, K.J.

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## Stanton 1940

- Stanton found the expansion of mortar bars was influenced by:
  - the alkali content of the cement
  - the type and amount of the reactive silica in the aggregate
  - the availability of moisture
  - temperature
- Other findings
  - Expansion was negligible when the alkali content of the cement was below 0.60% $Na_2O_e$
  - Expansion could be reduced by using pozzolans

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## Mechanism

- To have ASR you need:
  - sufficient quantity of reactive aggregate
  - sufficient concentration of alkali (mainly from cement)
  - sufficient moisture
- Take any one away and you can control the reaction

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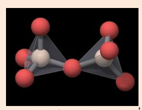
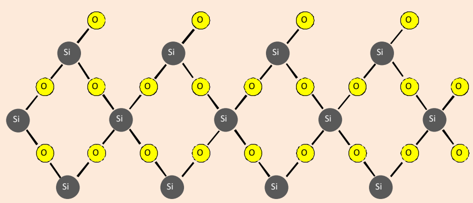
## Mechanism

- In the presence of pore solution ($H_2O$ and $OH^-$, $Na^+$, $K^+$, some $Ca^{2+}$), reactive silica undergoes depolymerization and dissolution
- Reaction product is a “gel” of Na, K, Ca, and Si
- The higher the pH, the more soluble the silica
- Gel imbibes water, expands, exerts tensile forces on surrounding concrete

- Silicon and oxygen prefer to combine in “tetrahedral coordination”
- Four (4) oxygens surround each silicon – open surface structure



Silica tetrahedra forming siloxane bond†



† http://www.quartzpage.de/gen_struct.html

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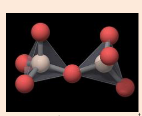

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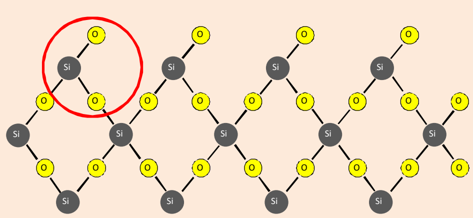

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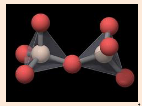

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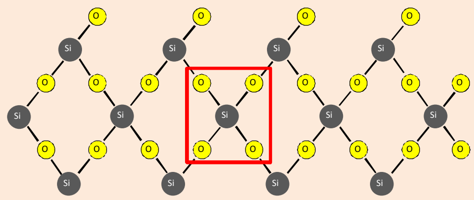

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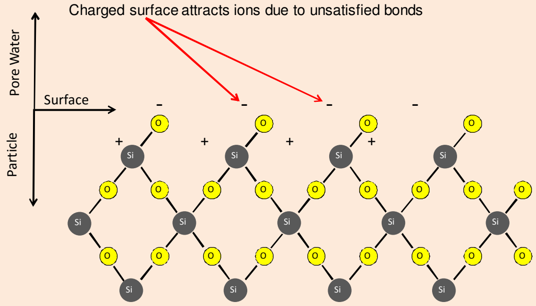
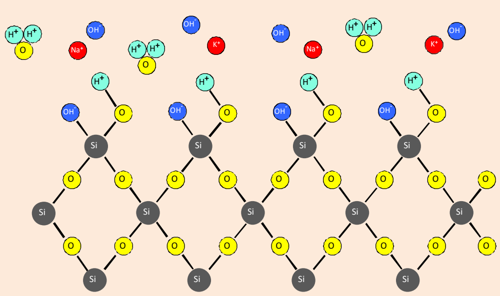
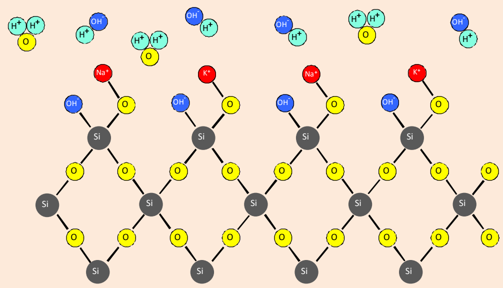
Charged surface attracts ions due to unsatisfied bonds



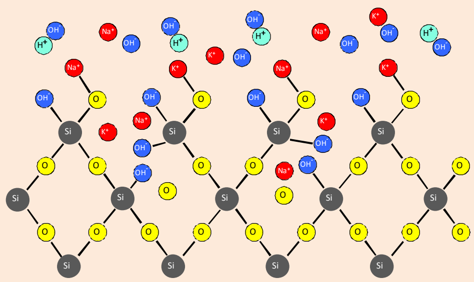

Charged surface attracts $H^+$ and $OH^-$ ions from alkali pore water



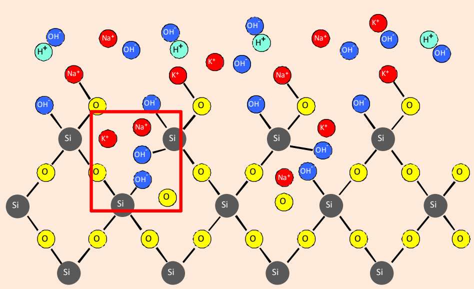
- With alkalis in pore water, $Na^+$ substitutes for $H^+$



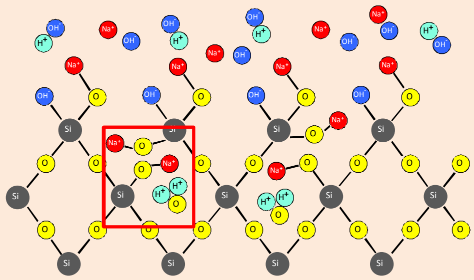
Hydroxyl associated with excess alkalis breaks the Si-O-Si bond and free an oxygen



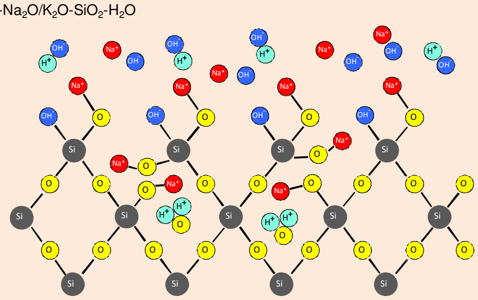
Hydroxyl associated with excess alkalis breaks the Si-O-Si bond and free an oxygen



Hydrogen dissociates from $OH^-$, combines with $O^{2-}$ to form water. $Na^+$ substitutes for $H^+$



- $Si\text{-}O\text{-}Si + 2OH^- + 2Na^+ \rightarrow 2(Si\text{-}O\text{-}Na) + H_2O$
- Eventually Si free, into solution – In the presence of Ca – Si precipitates as alkali silicate gel
- $CaO\text{-}Na_2O/K_2O\text{-}SiO_2\text{-}H_2O$



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## Why expansion?

- Back to history
  - Hansen (1944) – paste surrounding aggregate is semi-permeable membrane – water goes in, Si cannot come out – osmotic pressure
  - McGowan & Vivian (1952) – gel absorbs water and swells
  - Powers & Steinour (1955) – their both right

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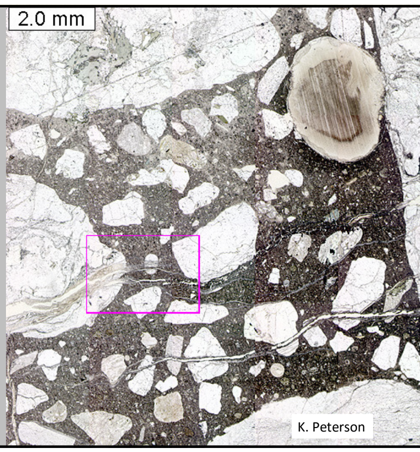
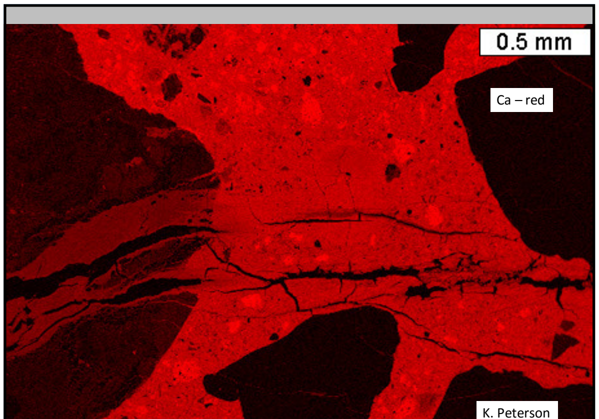
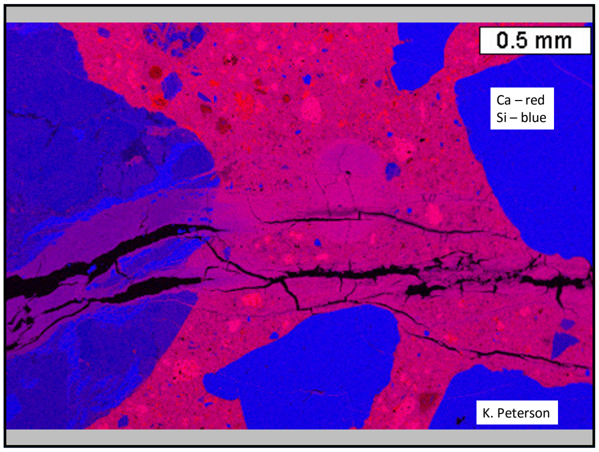
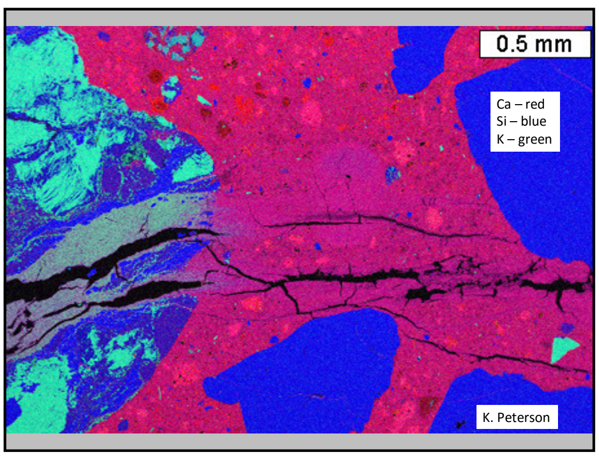
## Role of Calcium Hydroxide?

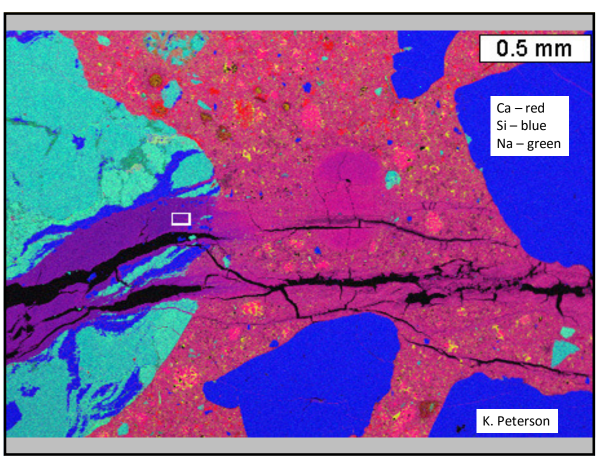
- Back to history
  - Hansen (1944), Thomas (2001) – calcium promotes alkali recycling
  - Wang & Gillot (1991) – calcium hydroxide provides supply of hydroxide ($OH^-$)
  - Thomas (1991, 1998) – calcium forms a gel that is itself a semi-permeable membrane

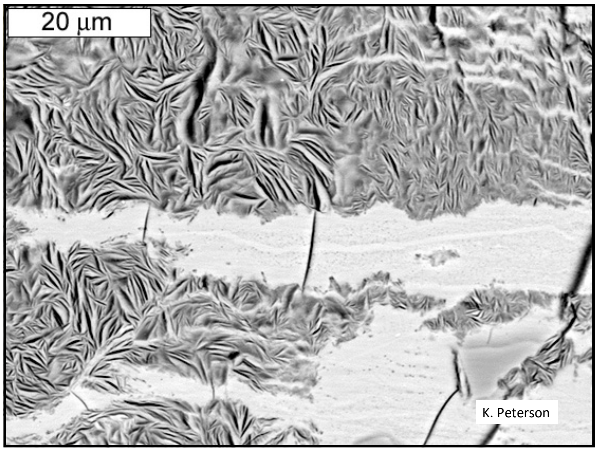



0.5 mm
Ca – red
Si – blue
K. Peterson


0.5 mm
Ca – red
Si – blue
K – green
K. Peterson


0.5 mm
Ca – red
Si – blue
Na – green
K. Peterson

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## What Do We Know?

- A lot of work has been done – a lot has been learned about ASR
- Calcium matters
- If we can reduce the calcium hydroxide we can control the expansion of mortars
- Many explanations for expansion – same result

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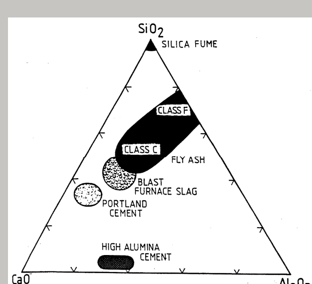
## Supplementary Cementitious Materials

- Pozzolans
  - Fly Ash
    - Class F – Pozzolanic
    - Class C - Cementitious
  - Silica Fume
    - Highly Pozzolanic
  - Natural Pozzolan
    - Variable
- Others
  - Slag Cement



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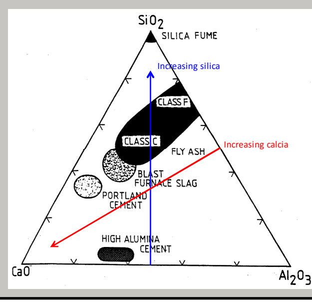


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## Testing to Evaluate Aggregates

- ASTM C295 Petrographic Examination
  - Identify specific minerals that may lead to ASR
  - Optical microscopy, XRD, SEM can all aid in identifying reactive minerals in the aggregate – but not all
  - Should not be used as the exclusive basis for accepting or rejecting aggregate

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## Testing to Evaluate Aggregates

- ASTM C1260 Mortar Bar Test
  - Quick (14 days)
  - Very severe test – creates false positives
  - Should not be used as the exclusive basis rejecting aggregate
  - Can also generate false negatives – pessimum effect

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## Pessimum Effect

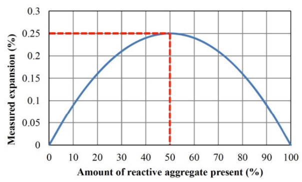


Figure 4.1. Graphical Representation of the 'Pessimum' Behavior Concept (adapted from Poole (1992) by Arrieta (2012))

Alkali-Aggregate Reactivity (AAR) Facts Book. Thomas, M.D.A., Fournier, B., Folliard, K.J.

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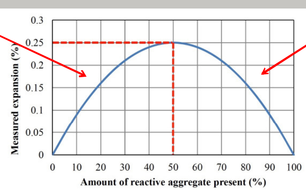
## Pessimum Effect

alkali > agg content

alkali < agg content

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## Testing to Evaluate Aggregates

- ASTM C1293 Concrete Prism Test
  - Currently the most reliable test available – not infallible
  - Not quick – one year minimum – two years if validating SCM replacement
  - Known drawbacks include alkali leaching that can lead to errors in estimating the alkali threshold need for ASR to occur

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## Testing to Evaluate Mitigation

- ASTM C1567 Accelerated Mortar Bar Test
  - Based on ASTM C1260
  - Cannot be used unless there is a reasonable correlation between C1260 and C1293 for the aggregate in question

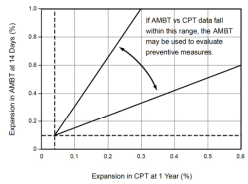


Figure 4.6. Comparison of AMBT and CPT Data for the Purpose of Determining Whether the AMBT is Suitable for Evaluating Preventive Measures with a Specific Aggregate (after AASHTO PP65-11)

Alkali-Aggregate Reactivity (AAR) Facts Book. Thomas, M.D.A., Fournier, B., Folliard, K.J.

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## Testing to Evaluate Mitigation

- ASTM C1293 Concrete Prism Test
  - Can be used in modified form to evaluate SCMs
    - Modifications include use of SCMs in place of OPC, HRWR and VMA admixtures if required
- ASTM C441 “Pyrex Bead” Test
  - Does not correlate well with concrete mixtures with natural aggregates
  - Used to specify SCMs (ASTM C618)

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## Pitfalls in Testing

- I have a brilliant idea. Let’s’ test the job mix!
- WRONG!
  - The tests use are intended to evaluate the material performance, not the mixture performance
  - Expansion criterion based on a specific quantity of the aggregate being tested. A job mix does not provide that specific quantity.
  - Can be fooled by the pessimum effect

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## Pitfalls in Testing

- If 14 days is good, the 28 days must be better
- If 0.10% expansion is good, then 0.08% must be better
- All ASR tests are **empirical tests**

Definition:

**Empirical (adj),** evidence or study that relies on practical experience rather than theories.

- **To be replicated empirical tests must be performed in the same manner, same conditions (i.e., empirically)**
- **Any number other than 0.10% at 14 days is absolutely meaningless**

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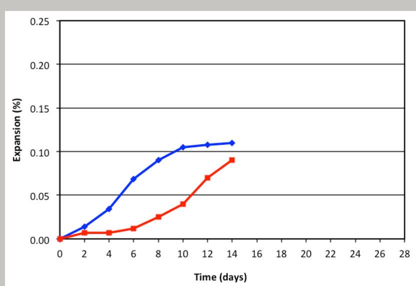
## C1260 Expansion at 14 Days

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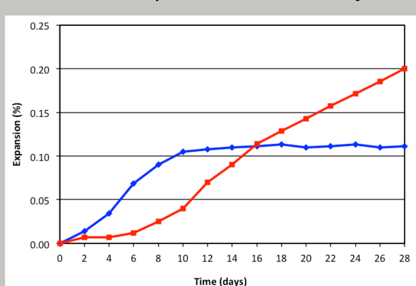
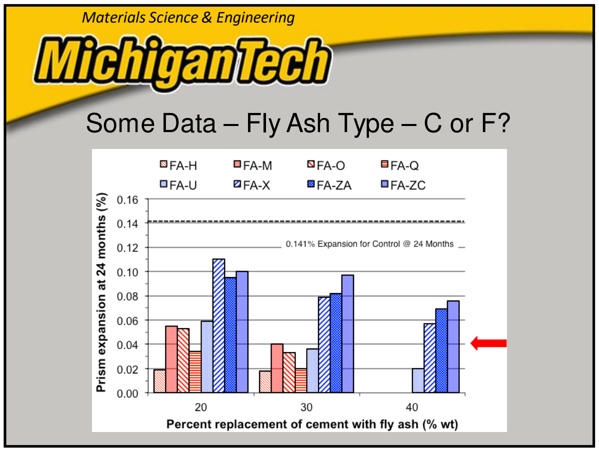
Current ASR tests do not account for the reaction kinteics, which is a big factor!

## C1260 Expansion at 28 Days

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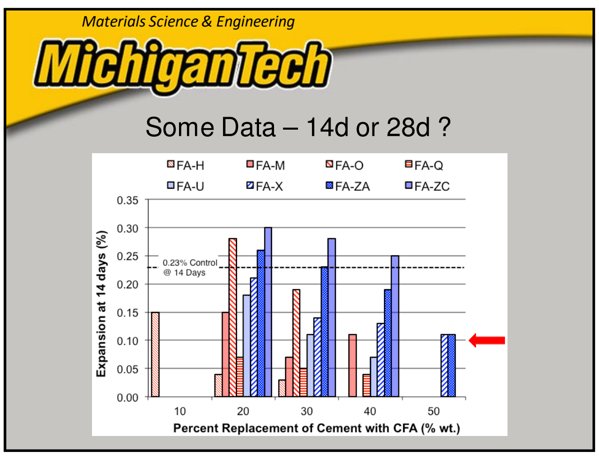
Some Data – Fly Ash Type – C or F?
FA-H
FA-M
FA-O
FA-Q
FA-U
FA-X
FA-ZA
FA-ZC
Prism expansion at 24 months (%)
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.141% Expansion for Control @ 24 Months
20
30
40
Percent replacement of cement with fly ash (% wt)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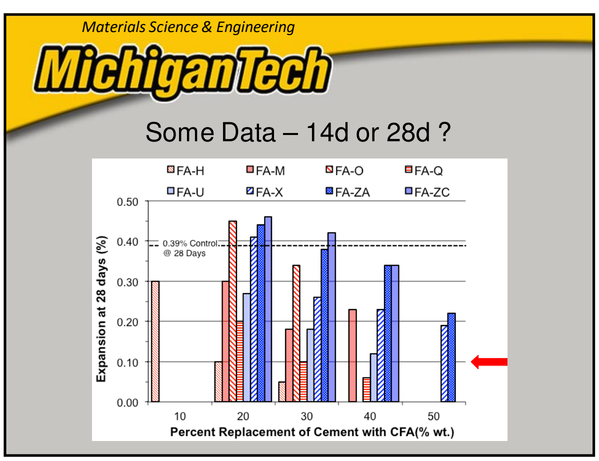
Some Data – 14d or 28d ?
FA-H
FA-M
FA-O
FA-Q
FA-U
FA-X
FA-ZA
FA-ZC
Expansion at 14 days (%)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.23% Control @ 14 Days
10
20
30
40
50
Percent Replacement of Cement with CFA (% wt.)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Some Data – 14d or 28d ?
FA-H
FA-M
FA-O
FA-Q
FA-U
FA-X
FA-ZA
FA-ZC
Expansion at 28 days (%)
0.50
0.40
0.30
0.20
0.10
0.00
0.39% Control @ 28 Days
10
20
30
40
50
Percent Replacement of Cement with CFA(% wt.)

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## Approaches

- AASHTO PP-65 *Standard Practice for Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction*
- ASTM C1778 *Standard Guide for Reducing the Risk of Deleterious Alkali-Aggregate Reaction in Concrete*

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## PP-65 and C1778

- Provide performance- and prescriptive-based approaches to:
  - Evaluating aggregate reactivity
  - Selecting mitigation approaches
- Starts with the obvious (field history) and systematically approaches evaluation and mitigation

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## PP-65 and C1778

- Considers all tests mentioned here today
- Summarizes the known best practices based on over 70 years of research history
- NOT PERFECT
- Assessment of risk and structure class is subjective so everyone picks the worse case – leads to over design

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## ASR Reactive Rocks & Minerals

| Rocks | | Minerals |
|---|---|---|
| Shale | Argillite | Opal |
| Sandstone | Granite | Tridymite |
| Silicified carbonate rock | Greywacke | Crisobalite |
| Chert | Silstone | Volcanic glass |
| Flint | Arenite | Cryptocrystalline quartz |
| Quartzite | Arkose | Strained quartz |
| Quartz-arenite | Hornfels | |
| Gneiss | | |

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## Now Aren't You Special!

- Minnesota is lucky to have their own special ASR actor
- The Pierre Shale
- Highly reactive - opal-cristobalite, siliceous micro-fossils
- Glacial deposited – Des Moines Lobe - The shale is mostly found in moraines, and in the fluvial deposits derived from moraine material
- It is paractically impossible to find a sand without some reactive shale included

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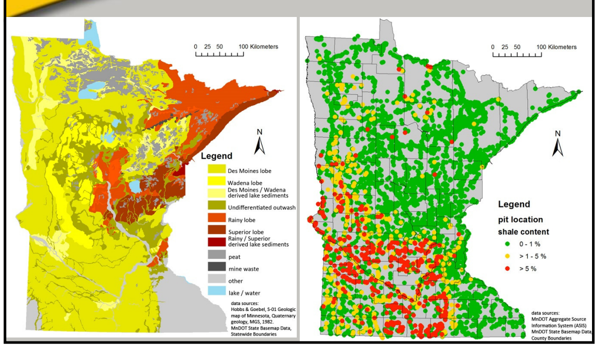
Maps Produced by
Dr. Karl Peterson
University of Toronto



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## Shale Popouts

- The shale reacts very quickly (for ASR)
  - First hours, maybe days
- Tends to react when concrete is fresh or when pore structure not fully developed
  - Gel can move without creating pressure
- Issues occur at surface

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## Shale Popouts

- Alkali concentrates at surface as bleed rises, water is lost to dehydration
- Concentrated alkalis accentuate the ASR reaction
- Gel produced faster than can be accomodated
- No restraint – popouts
- SCMs (fly ash) will not help – pozzolanic reaction lags the shale reaction

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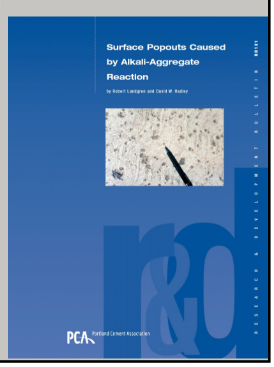
PCA Publication RD 121

http://tinyurl.com/pierre-shale

*also*

Dobie, 1986



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## Shale Popouts - Prevention

- The shale is ubiquitous – it cannot be avoided – some popouts will always occur
- Minimized by:
  - Low-alkali cement
  - Avoide the surface drying out (keep wet, flooded)
  - Avoid hard troweling
  - Protect from drying before troweling (polyethylene)
  - Low cement content
  - Air entrainment

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## Closing

- Aggregates constitute the largest volume of concrete
- Aggregate properties (mineralogical and chemical) dictate "good" and "bad" aggregates
- Most (not all) aggregate related problems can be mitigated once the problem is understood
- Mitigation may mean selection, processing, or changes to mixture designs

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## Closing

- Like most concrete tests – aggregate tests are not without flaws
- Unlike the stock market – **past performace is an indicator of future performance**
- When applying existing tests – use them as written
- You will never get a perfect aggregate source – Mother Nature is a bitch…

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## Questions?

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