AGGREGATES AND POZZOLANIC MATERIALS OVERVIEW

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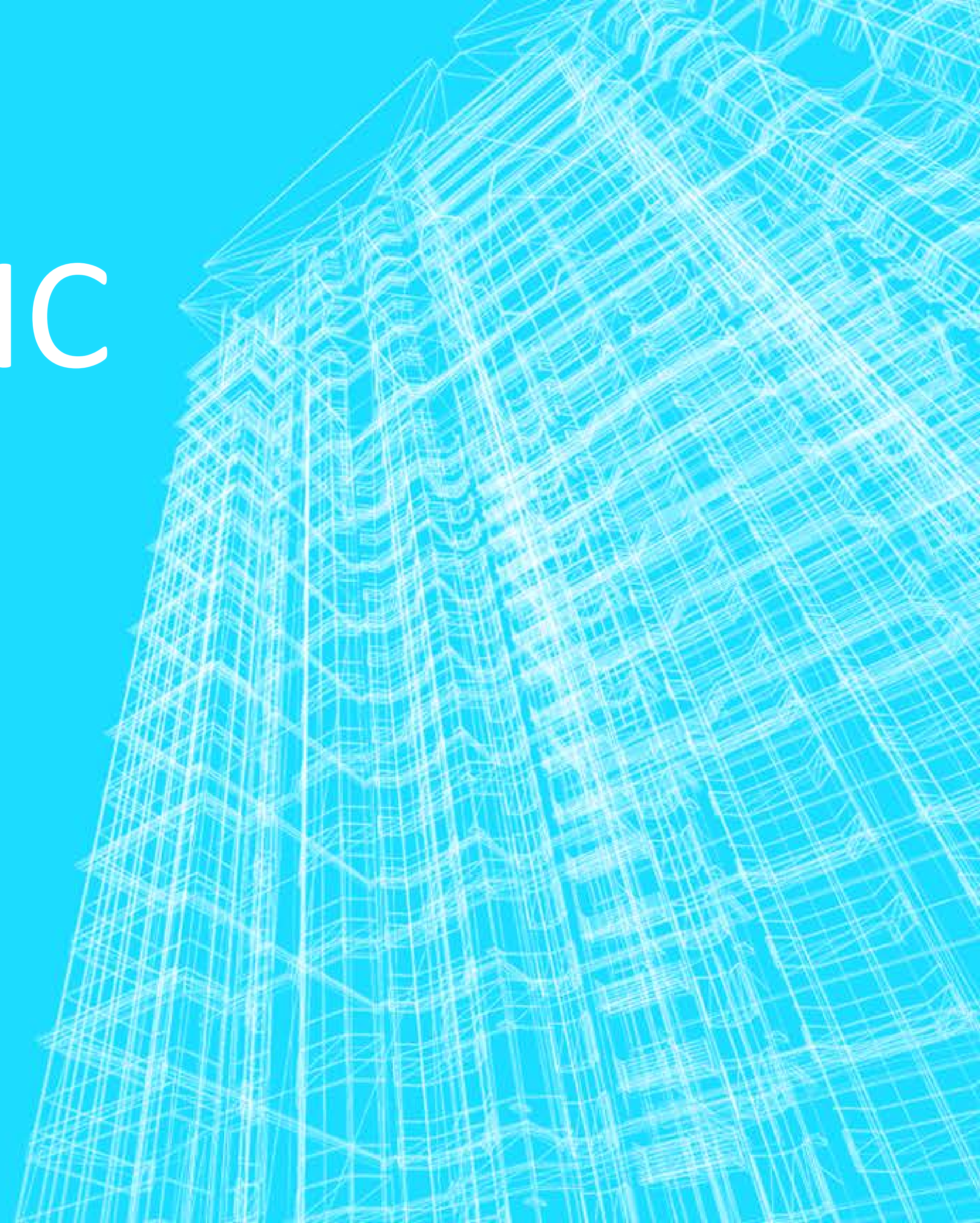
April 10, 2018



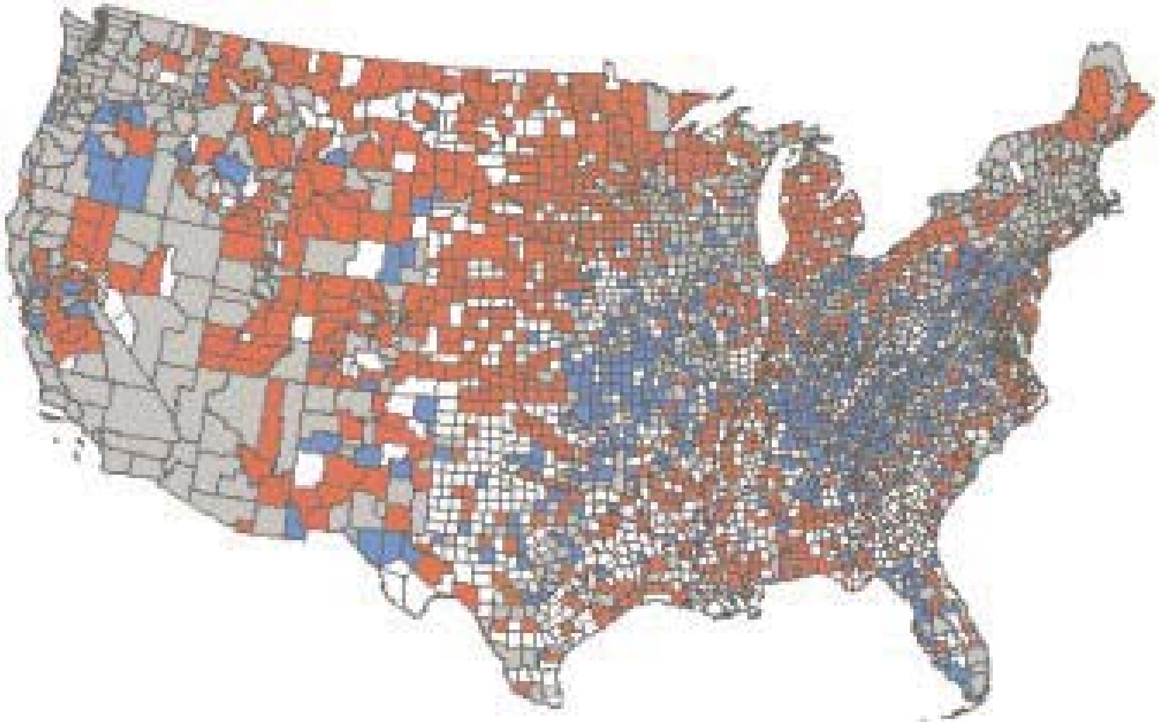
OVERVIEW OF AGGREGATES

What are Aggregates and Why do We Need Them?

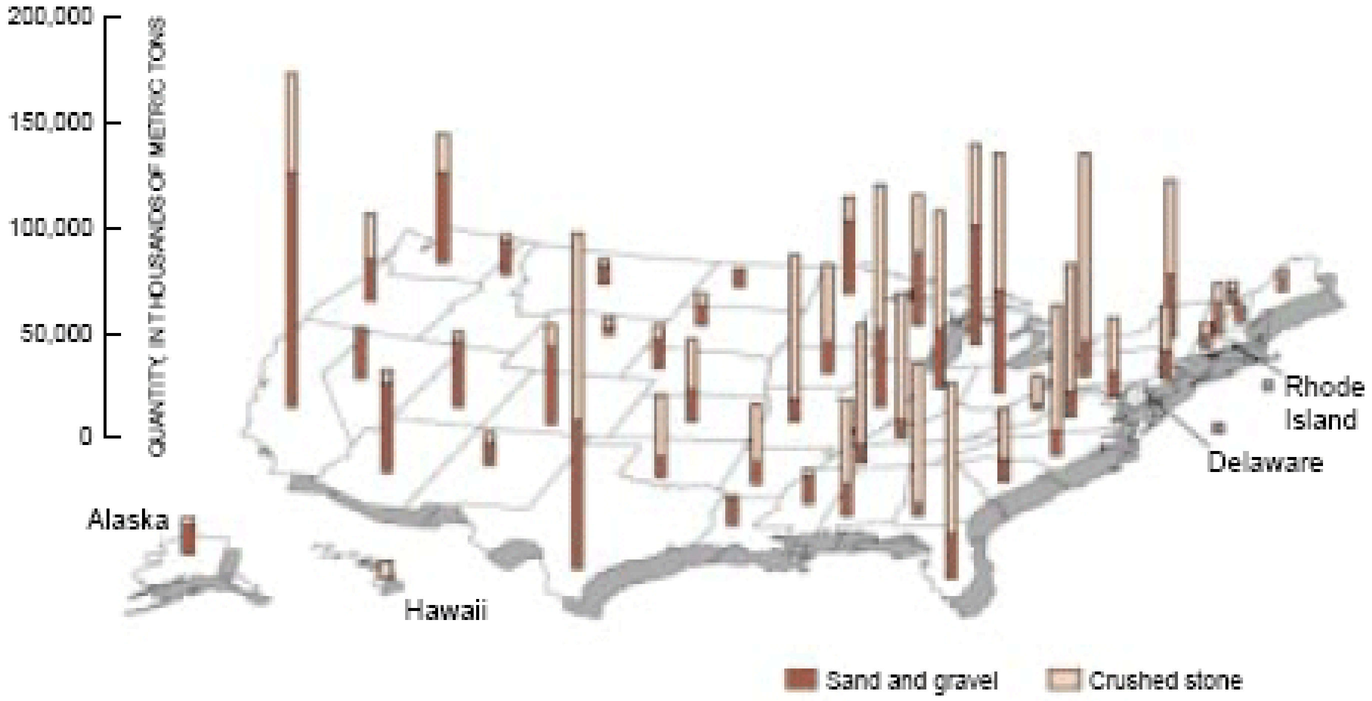
- Aggregates are cost effective and stable fillers for concrete.
  - Aggregates contribute to strength of hardened concrete and are stronger than the cement itself.
  - Aggregates are volumetrically stable.
  - Aggregates are typically locally sourced and as such are inexpensive. Cost is the driving factor in aggregate selection.

AGGREGATES

- Aggregates generally occupy 70 to 80% of concrete volume $\Rightarrow$ They are expected to have an important influence on its properties.
- Physical, thermal, chemical properties of aggregate influence the performance of concrete
- Aggregates are derived for the most part from natural rocks (crushed stone, or natural gravels) and sands.
- <u>Aggregate characteristics vary according to regional geology.</u>



CRUSHED STONE OR SAND AND GRAVEL?



Limestone/Dolomite 71%
Granite 15%
Traprock 8%
Others 6%
2017 USGS Natural Aggregates Report

AGGREGATES

- Aggregate is cheaper than cement $\Rightarrow$ Economical to use in the mix, higher volume stability, and better durability.

- Acceptable aggregates must conform to ASTM C 33 or similar spec.

AGGREGATES

- Aggregates should be hard and strong, free of undesirable impurities, and chemically stable.
  - Soft and porous rock can limit strength, wear resistance, and workability.
  - Aggregates should be free of impurities: Silt, clay, dirt, or organic matter.

PROPERTIES REQUIRED FOR MIX DESIGN

- To proportion suitable concrete mixes, certain properties of aggregate must be known:

  (1) shape and texture

  (2) size gradation

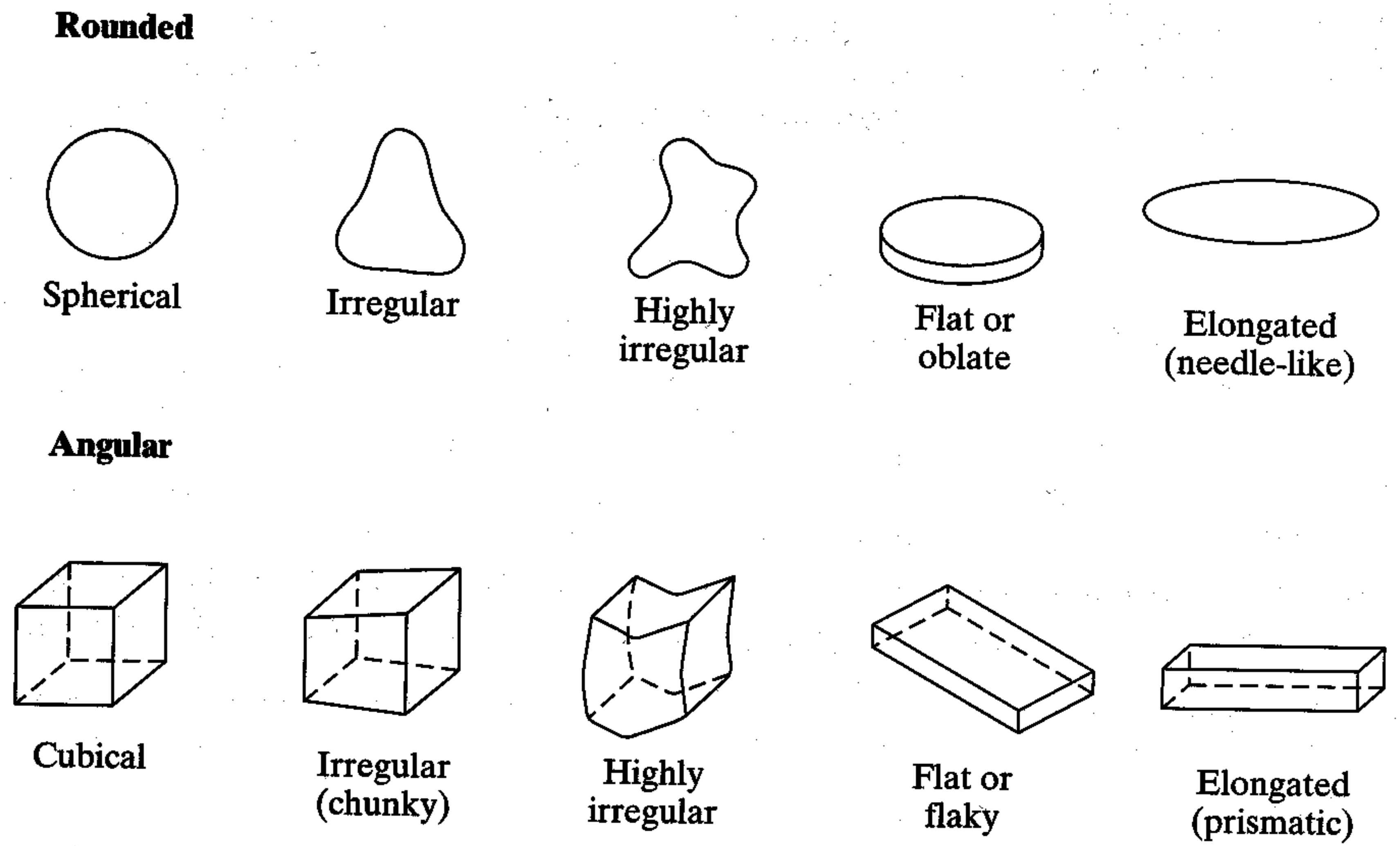
  (3) moisture content

  (4) absorption

  (4) specific gravity

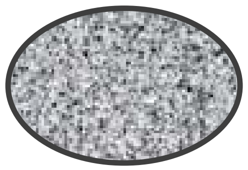
  (5) bulk unit weight.

CLASSIFICATION OF AGGREGATE SHAPES

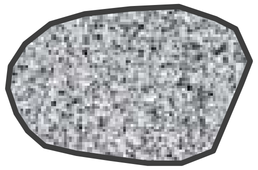


PARTICLE SHAPES

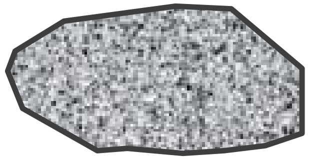
- Rounded



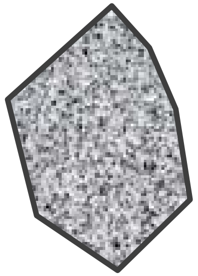
- Sub-Rounded



- Sub-Angular

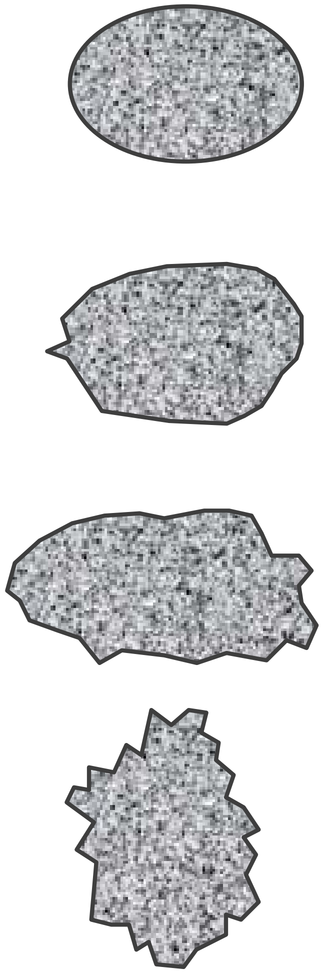


- Angular



SURFACE TEXTURES

- Polished
- Smooth
- Rough
- Very Rough



SHAPE AND TEXTURE

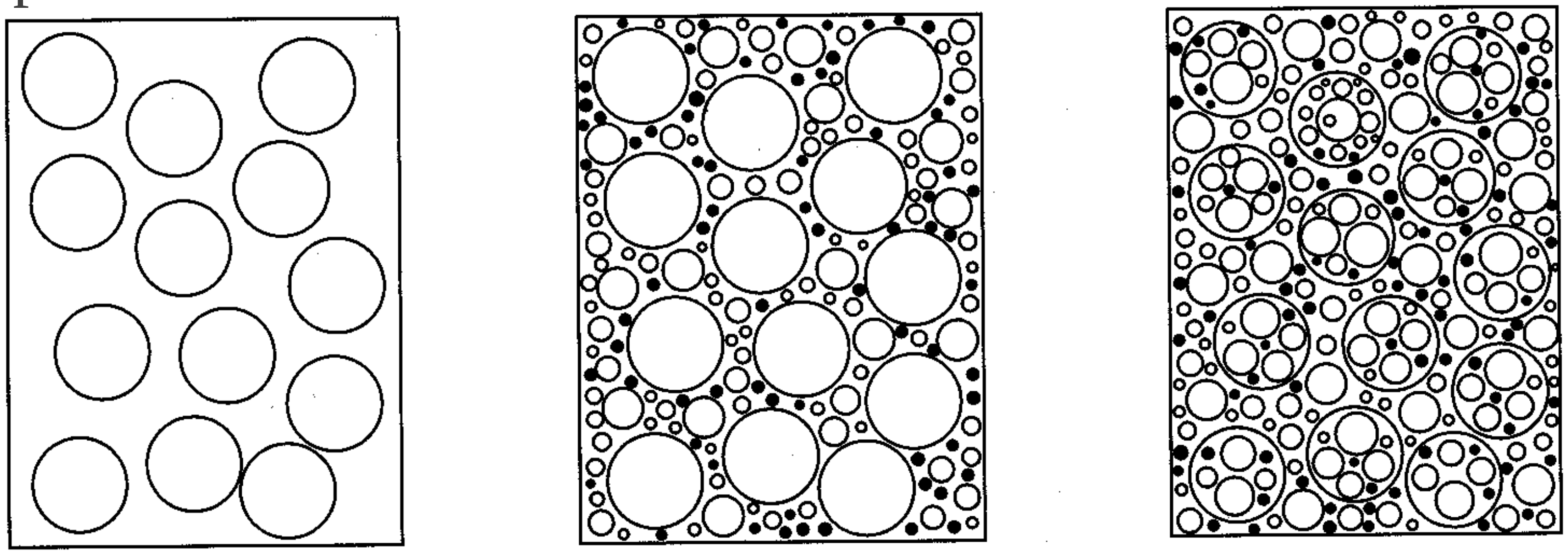
- Crushed stone is more angular and has a high surface-to-volume ratio $\Rightarrow$ Require more paste to fully coat surface.
- Flat or elongated aggregates should be avoided because they increase particle interaction and they have a high surface-to-volume ratio – They are also prone to segregation during handling.

SIZE GRADATION

- Particle size distribution or grading of an aggregate is important since it determines the paste requirements for a workable concrete.
- It is desirable to minimize cost of concrete by using the smallest amount of paste consistent with the production of a concrete that can be handled, compacted, and finished and provide the necessary strength and durability. Modern changes to gradation specifications have favored workability over paste reduction.

SIZE GRADATION
(A) UNIFORM SIZE (B) CONTINUOUS GRADING
(C) REPLACEMENT OF SMALL SIZES BY LARGE SIZES.

- Volume of voids between roughly spherical particles is greatest when particles are of uniform size.
- When range of sizes is used $\Rightarrow$ Smaller particles pack between larger.
- Using larger max. size can also reduce the void space and paste content.



(a) (b) (c)

GRADING CURVES

- ASTM C33 sets grading limits for fine and coarse aggregate based on practical experience.

ASTM Grading Limits for Fine Aggregates[b]

Sieve Size	*% Passing*[a]
9.5 mm ($\frac{3}{8}$in.)	100
4.75 mm (No. 4)	95–100
2.36 mm (No. 8)	80–100
1.18 mm (No. 16)	50–85
600 μm (No. 30)	25–60
300 μm (No. 50)	5–30
150 μm (No. 100)	0–10

GRADING CURVES

- If aggregate does not conform to ASTM C33 grading limits ⇒ It does necessarily mean that concrete can't be made with the aggregate. It means that concrete may require more paste and is more liable to segregate.

ASTM Grading Limits for Coarse Aggregates[b]

Size Number[a]	*Nominal Max. Size*	*% Passing Each Sieve* 63 mm ($2\frac{1}{2}$ in.)	50 mm (2 in.)	37.5 mm ($1\frac{1}{2}$ in.)	25 mm (1 in.)	19.5 mm ($\frac{3}{4}$ in.)	12.5 mm ($\frac{1}{2}$ in.)	9.5 mm ($\frac{3}{8}$ in.)	4.75 mm (No. 4)	2.36 mm (No. 8)	1.18 mm (No. 16)
357	50 mm (2 in.)	100	95–100	...	35–70	...	10–30	...	0–5	...	...
467	37.5 mm ($1\frac{1}{2}$ in.)	...	100	95–100	...	35–70	...	10–30	0–5	...	...
57	25 mm (1 in.)	...	...	100	95–100	...	25–60	...	0–10	0–5	...
67	19 mm ($\frac{3}{4}$ in.)	...	...	...	100	90–100	...	20–55	0–10	0–5	...
7	12.5 mm ($\frac{1}{2}$ in.)	...	...	...	...	100	90–100	40–70	0–15	0–5	...
8	9.5 mm ($\frac{3}{8}$ in.)	...	...	...	...	...	100	85–100	10–30	0–10	0–5

MOISTURE CONTENT AND ABSORPTION

- Water can be absorbed into aggregate due to the aggregate porosity. This is a function of source geology and crushing.
- Water can be retained on the surface of aggregate particle as a film moisture.
- If aggregate is dry $\Rightarrow$ It will absorb water from the paste so that w/c is lowered and workability decreased.
- If excess water is present at aggregate surfaces, extra water will be added to the paste and w/c will be higher.

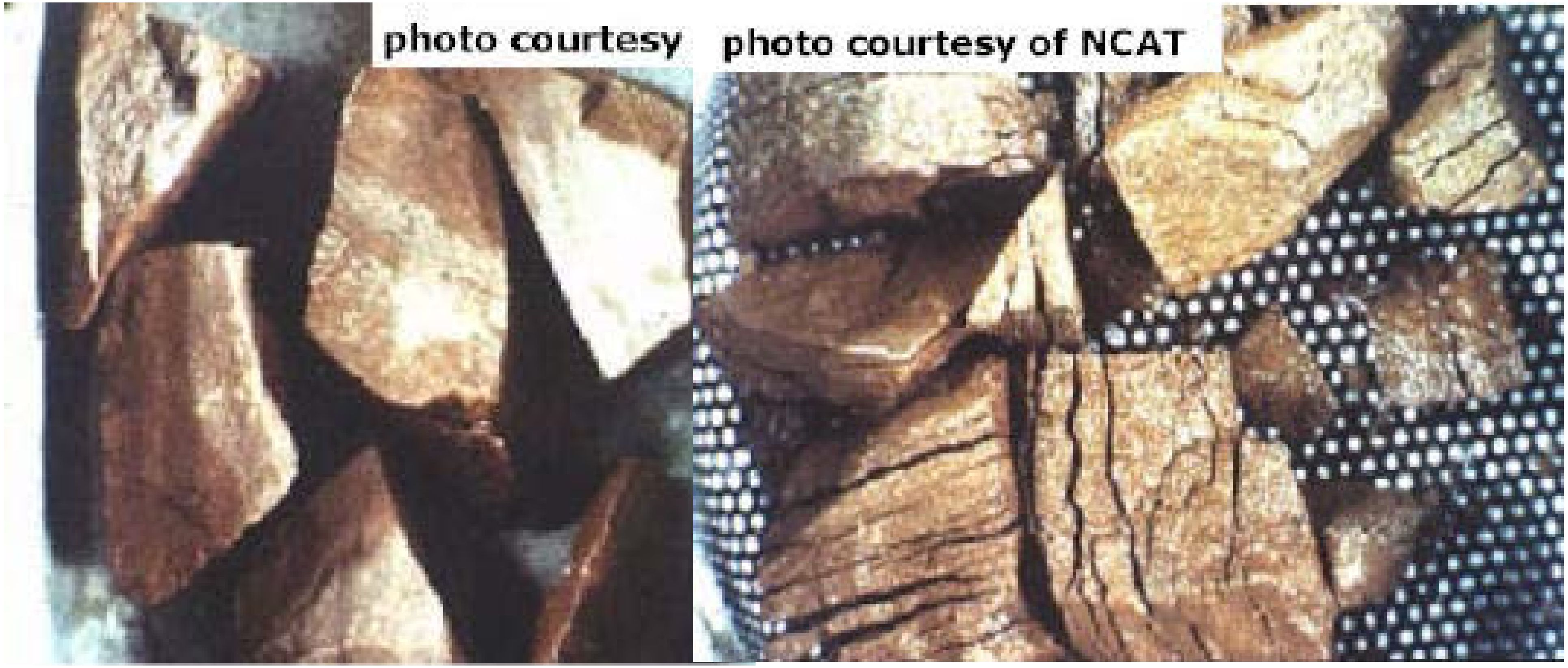
DURABILITY OF AGGREGATES

- Aggregates make up the bulk of concrete, and a lack of aggregate durability will have disastrous consequences for the concrete.
- Lack of aggregate durability can be divided into:
  - Physical causes (Susceptibility of aggregates to F&T or wetting and drying, as well as physical wear).
  - Chemical causes (Various forms of cement-aggregate reactions).

PHYSICAL DURABILITY
SOUNDNESS

- Aggregates are unsound if volume changes that accompany environmental changes lead to concrete deterioration.
- Volume changes can arise from:
  - Alternate freezing and thawing
  - Repeated wetting and drying (very rare)
  - Alkali Silica Reaction
- Unsoundness of aggregate due to F&T leads to:
  - Surface pop-outs
  - D-cracking

SOUNDNESS
BEFORE AND AFTER CONDITION



PHYSICAL DURABILITY
WEAR RESISTANCE

- Aggregate plays an important role in the resistance of concrete to surface abrasion and wear.
- Good aggregate is hard, dense, strong, and free of soft, porous, or friable particles.
- Abrasion resistance of aggregate can be tested by the Los Angeles test (ASTM C131 and C535).
- Micro-Deval test (CSA A23.2-23A) – similar to LA Abrasion but it is more severe since aggregate is wet

CHEMICAL RESISTANCE

- Most chemical durability problems result from a reaction between reactive silica in aggregates and alkalis contained in the cement.
- Most familiar problem: alkali-aggregate reaction (alkali-silica reaction or ASR).
- Other chemical distresses:
  - Iron pyrites (FeS) may react expansively in presence of calcium hydroxide $\Rightarrow$ Popouts and staining.
  - Natural gypsum causes sulfate attack if present in significant amounts.
  - Zinc or lead found in aggregate deposits may greatly delay setting and early hardening of cement.

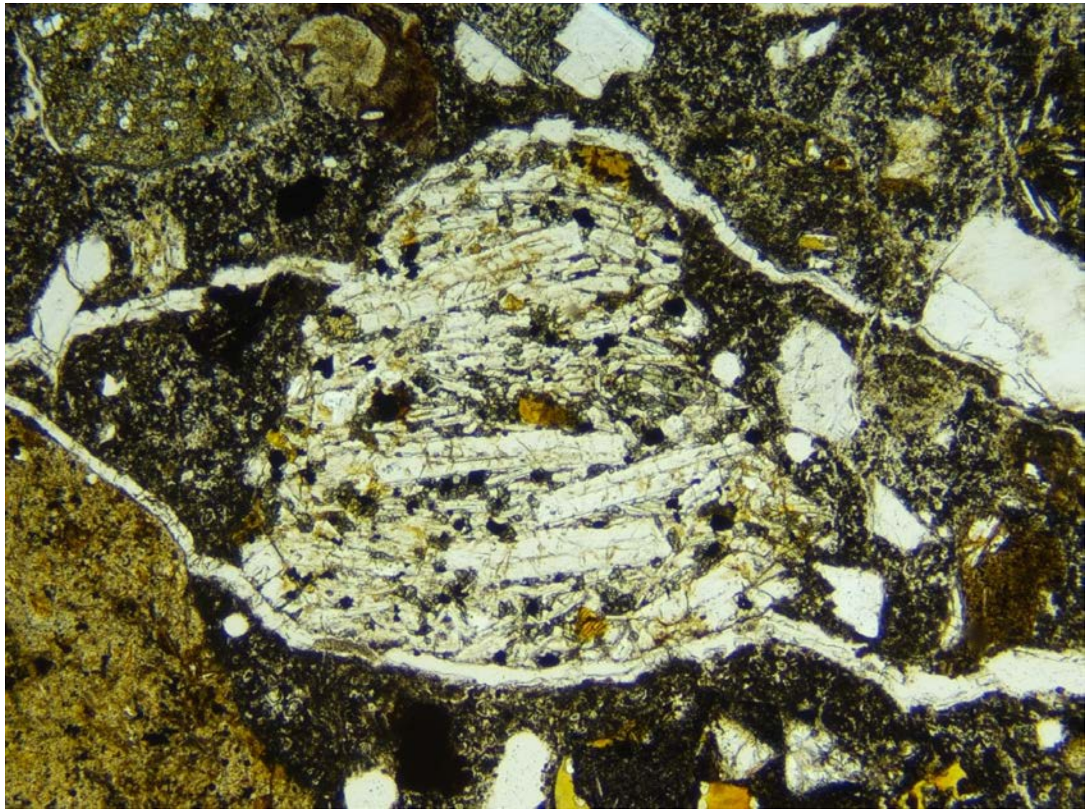

Estwing

FORMS OF REACTIVE SILICA IN ROCKS

Forms of Reactive Silica in Rocks That Can Participate in Alkali–Aggregate Reaction

Reactive Component	*Physical Form*	*Rock Types in Which It Is Found*	*Occurrence*
Opal	Amorphous	Siliceous (opaline limestones, cherts, shales, flints)	Widespread
Silica glass	Amorphous	Volcanic glasses (rhyolite, andesite, dacite) and tuffs; synthetic glasses	Regions of volcanic origin; river gravels originating in volcanic areas; container glass
Chalcedony	Poorly crystallized quartz	Siliceous limestones and sandstones, cherts and flints	Widespread
Cristobalite tridymite	Crystalline	Opaline rocks, fired ceramics	Uncommon
Quartz	Crystalline	Quartzite, sands, sandstones, many igneous and meta-morphic rocks (e.g., granites and schists)	Common, but reactive only if highly strained or microcrystalline

ASR IN HARDENED CONCRETE SECTION



CONTROL OF ALKALI-AGGREGATE REACTION

- Adequate protection is typically attained by replacing portions of cement by Supplemental Cementitious Materials.
- Silica fume is highly effective (10 to 15% are typical).
- Natural Pozzolans are highly effective (25 %)
- When slag is used, replacement quantities of 50% or more are common.
- Low-alkali cements , blended cements such as Type IP and IS control the alkali-aggregate reaction.

CONTROL OF ALKALI-AGGREGATE REACTION

- Alkalis can come, not only from cement, but also from chemical and mineral admixtures and from the aggregate itself $\Rightarrow$ Total alkali content in concrete gives a better figure.
- Upper limit for total alkalis when reactive aggregates are used = 5-lb/yd^3 (3 kg/m^3).
- Low w/c is very impermeable $\Rightarrow$ Limit supply of water needed to cause alkali-silica gel to swell, but this will only slow the reaction.

RISKS TO THE AGGREGATE INDUSTRY

- Primary focus is on cost including aggregate production costs and transportation costs. Performance and long-term durability are second and third tier drivers for aggregate selection.
- Misunderstood specifications and testing – we are seeing trends to screen out potentially reactive aggregates through misapplication of tests including C1260 and C1567. This is a regressive approach toward managing durability.
- We have lost a generation of engineering geologists and petrographers and universities are not making more. This leads to unrealistic performance expectations and a lack of understanding of the influence of parent geology or depositional environments.
- Narrowing education for practicing engineers.
  - Most graduate civil engineers NEVER have a class on aggregates and rarely have a course in geology. Often times aggregates are treated as an off-the-shelf part rather than a complex actor in concrete. Most civil engineers have a single semester of materials that includes 8-classroom hours of instruction on Portland cement concrete!

NEED FOR FURTHER WORK

- Research needs for aggregates in concrete
  - Internal Curing
    - Can high absorption aggregates be managed as internal water reservoirs to promote curing?
  - Recycled Aggregates
    - Performance and volumetrics of crushed recycled concrete, recycled glass aggregates, slag aggregates are poorly understood resulting in reduced opportunities for re-use in concrete.
  - Pozzolanic or Matrix Engaged Aggregates
    - The current system for concrete mix design treats aggregates and cementitious material as mutually exclusive components. Can a Roman Style system be utilized where the aggregates themselves provide controlled reactions to engage with the cementitious matrix and contribute to a living, self healing system? Can pozzolanic aggregates and Roman principles be utilized in a predominately OPC system?

POZZOLANS

SURVEY OF CEMENTITIOUS MATERIALS

- **CEMENT** Supplies are Tightening Across the Western US.
  - Domestic manufacturing is nearly at capacity. Asian imports have been prominent in western markets for over 2 years.
  - Even with more industry friendly regulators, adding new plant capacity is not realistic due to capital and environmental permitting requirements (NIMBY).
  - In addition to tightening supply, specifiers are actively changing performance criteria for cements.
    - Longer project design life
    - Higher, earlier strength development for fast-track projects
    - Higher durability standards (better resistance to chemical and physical attack)
    - Focus on carbon accounting through specification and even legislation

SURVEY OF CEMENTITIOUS MATERIALS

- **FLYASH** Supplies are also Tightening Across the Western US.
  - Domestic supply is diminishing rapidly due to power plant closures.
  - Even with more industry friendly regulators, maintaining current supply level is not realistic due to aggressive price competition from natural gas.
  - Tighter emissions controls is increasing carbon content of many ashes, making them unsuitable for use in concrete.
  - In response to shrinking supply, producers are actively working to change definitions and specifications of flyash for use in concrete.
    - ASTM 618 Committee recently voted to change Class F versus Class C designation to CaO basis.
    - This effort will increase the number of sources that qualify as “F” ash and eventually eliminate the distinction.

SURVEY OF CEMENTITIOUS MATERIALS

INDUSTRY IS ACTIVELY WORKING TO ADDRESS CURRENT MARKET DYNAMICS THROUGH RESEARCH AND DEVELOPMENT OF NEW PRODUCT OFFERINGS

- ASTM C 595 Blended Cements
  - Type IL
  - Type IP
- Development of New Supplemental Cementitious Materials
  - Natural Pozzolans - C618
  - Ground Glass Pozzolans – C 09.24 Provisional Standard
  - Blended Pozzolans - C1697-16

WHAT IS A POZZOLAN?

- Finely divided siliceous material
- Alkali soluble (glassy)
- Little to no active clays
- Typically coal ash, iron slag, volcanic ash or pumice, diatomaceous earth, or calcined clays
- NPs and slag tend to have higher aluminum oxides than coal ash (>10%)

WHAT IS A POZZOLAN?

- POZZOLANS REACT WITH EXCESS PORTLANDITE IN CONCRETE TO CREATE CALCIUM SILICATE HYDRATES.
  - This secondary reaction is desirable to increase density and decrease permeability of the hardened concrete.
  - Pozzolans can help to mitigate potentially reactive aggregates.
  - Pozzolans can increase workability without added water.
  - Pozzolans can reduce the carbon footprint of concrete by cutting out cement. Typical values are up to 25 percent replacement.
  - Pozzolans are economical and typically result in cost savings to concrete.
    - Pozzolans range in price from 40-85 percent of the cost of cement.

NATURAL POZZOLANS

- Currently the US Consumes Approximately 500,000 TPY of Natural Pozzolans
- Approximately 35 percent of that material is manufactured in Nevada!
- Approximately 1.5M TPY of supply is in the pipeline for completion by 2019
- This material will be the primary SCM for the Western US inside of 10 years

NATURAL POZZOLAN ASSOCIATION

HISTORY OF NATURAL POZZOLANS

- Natural Pozzolans have been used for millennia
- Ancient Greeks used alkali activated cements at Keimeros and Rhodes in 500 AD.
- Romans perfected the use of pozzolan/lime systems in the period between 300 BC and 400 AD.
    - Romans utilized sophisticated materials specifications and mix design methods for specific applications.
    - Pozzolana was valued and high performing materials were exported throughout the Mediterranean for military and public works projects.

CURRENT STATE OF MATERIAL

- Natural Pozzolans are once again becoming attractive to specifiers for a variety of reasons.
  - Availability
  - Predictable and repeatable properties including color
  - High performing in specialty applications
    - ASR
    - Sulfate Attack
    - Acid Attack
  - Proximity to West Coast
  - COST
  - Environmentally attractive
    - Low carbon footprint (no coal stigma)
    - Low metals profiles

TYPES OF NATURAL POZZOLAN

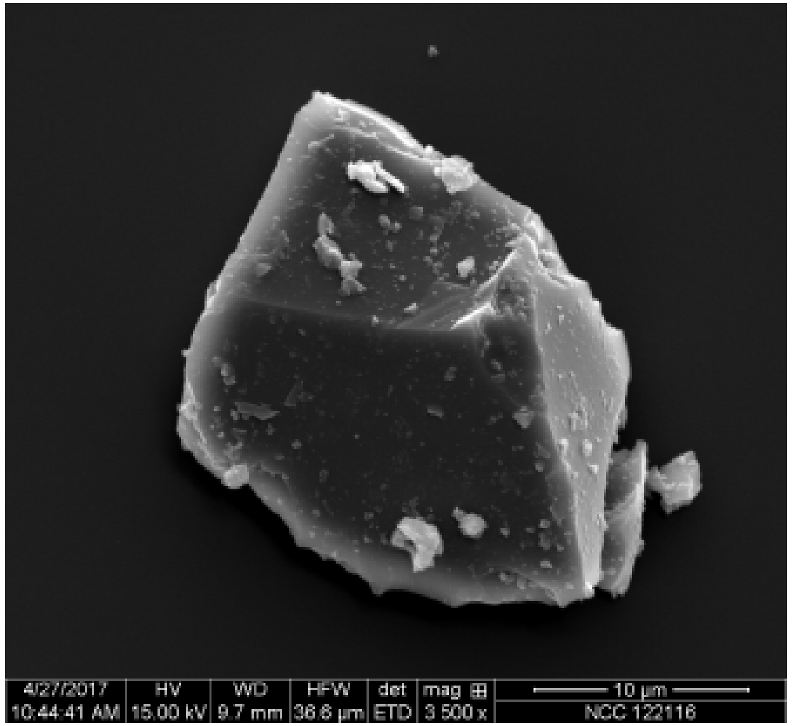
- Calcined
  - Thermally processed to increase performance characteristics 700-900 C
  - Destroys clay species
  - Changes particle morphology and reduces surface area
    - Includes Diatomaceous Earths
    - Calcined Clays
  - High performance potential (metakaolin)
  - Higher Carbon Footprint

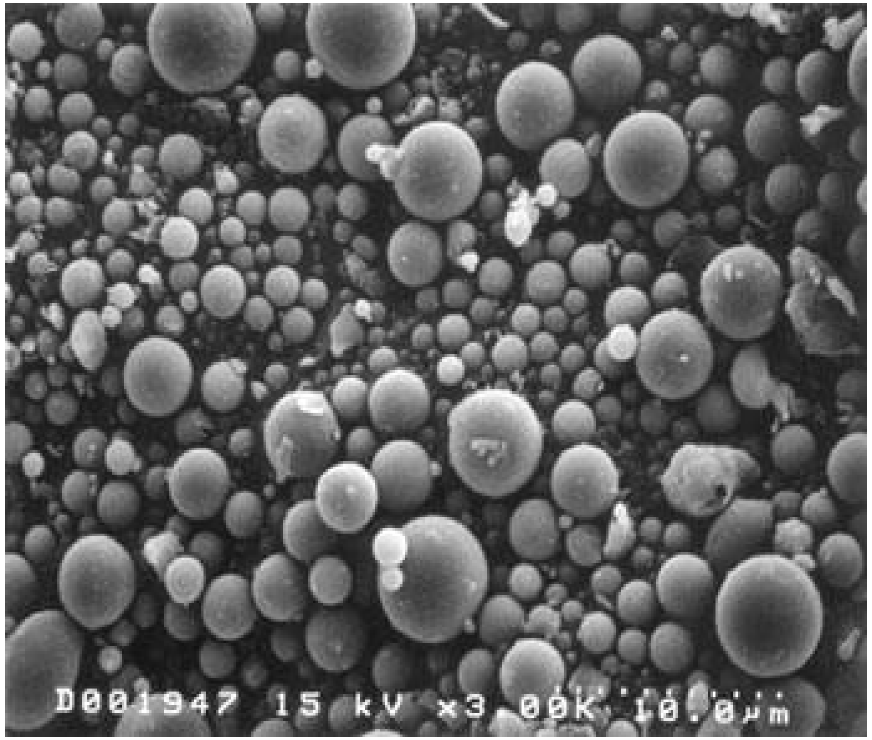
- Raw Ground
  - Natural volcanic ash sources
  - Mined and ground without thermal processing
  - Typically lowest carbon footprint

NATURAL POZZOLAN PERFORMANCE

- Water demand
  - Particle morphology differs from flyash
- Slightly Lower early-day strength
- Normal long-term strength
- Excellent reduction in permeability
- Excellent bleed water reduction
- Excellent ASR Performance
- Excellent Sulfate and Acid Performance
  - Higher formation of C-A-S-H than other pozzolans due to Si/Al ratio

NP VERSUS FLYASH





HISTORY OF NATURAL POZZOLAN

- Pozzolanic or “Roman” cements were utilized throughout the centuries with renewed interest in the 18th and early 19th centuries.
- Portland Cement Concrete largely replaced “Roman” cement by 1900 when pozzolans began to assume a new role.
- Many of the great public works project of the early 20th century included natural pozzolans.
- Use of natural pozzolans began to fade in the 1960’s as flyash supply became readily available and marketed.

CURRENT STATE OF MATERIAL

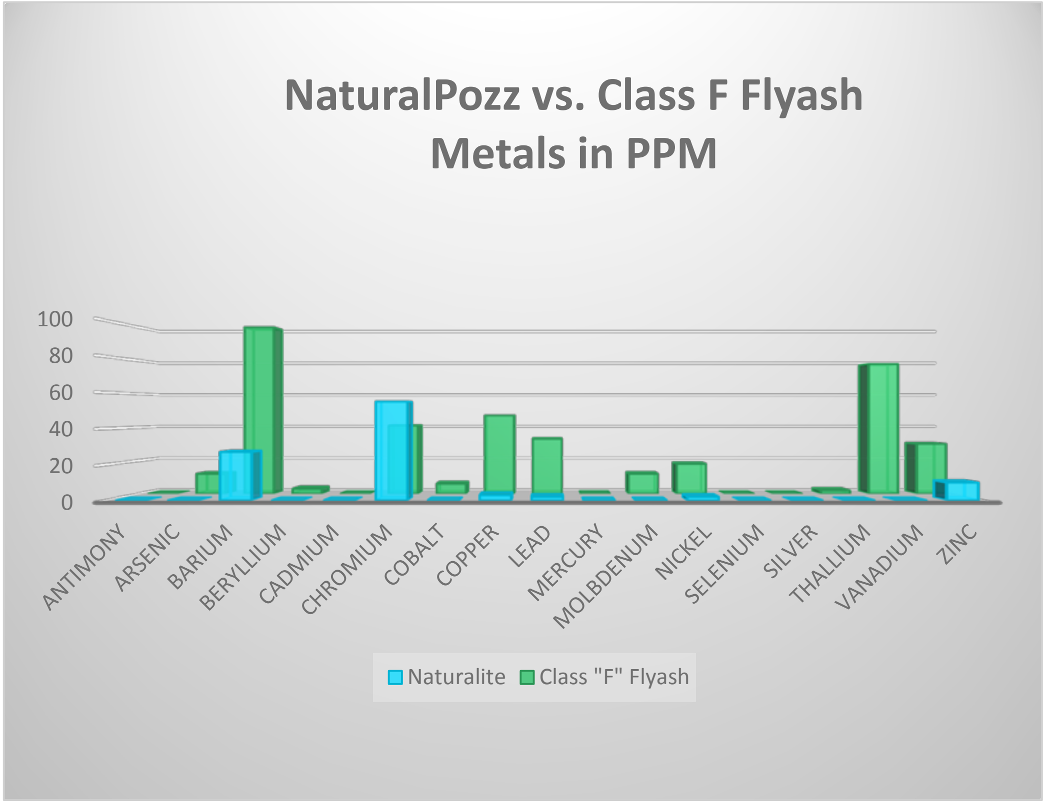
- Natural Pozzolans are once again becoming attractive to specifiers for a variety of reasons.
- National Sales Volumes were approximately 500K tons in 2017
  - Approximately 100K tons in California
  - Balance sold in Nevada, Utah, oil fields, and specialty
- According to PCA, approximately 350K tons of Type IP cement produced in 2017
- Natural Pozzolan Association has gained 501c6 Status and is increasing membership monthly.

CURRENT STATE OF MATERIAL

- A small number of active raw ground pozzolan producers – 300K TPY
  - Nevada Cement, CR Minerals, Hess Pumice
- Calcined Clays are available but typically specialty and higher cost – 200K TPY
  - Burgess Pigments, BASF
- A small field of junior/independent producers are developing projects
  - Kirkland Mining, Geofortis, SR Minerals, Pinyon
- Natural Pozzolans have captured the attention of larger players
  - Eagle Materials, SRMG, Lafarge Holcim, Boral Materials, CalPortland, 3M, Haliburton

NATURAL POZZOLAN PERFORMANCE

- Excellent bleed water reduction
- Excellent Air Stability
- Excellent ASR Performance
- Environmentally sound
  - Low Carbon footprint
  - No Coal Stigma
  - Very low metals profile
- Excellent Sulfate and Acid Performance
  - Higher formation of C-A-S-H than other pozzolans due to Si/Al ratio



SUMMARY

- BIG CHANGES are coming to cementitious materials in the next decade
  - Materials are changing due to economic, material performance, and environmental drivers
  - Industry forces are responding through aggressive R&D of “new” products to ensure supply stability
  - Changes to material formulary should have a net positive effect on concrete durability

MORE WORK IS NEEDED

- Research needs for expanded understanding of Natural Pozzolans as their market share continues to grow.
  - Mechanisms of glass dissolution
  - Formation of CASH binders
  - Pozzolanic management of reactive aggregates
  - High Volume pozzolanic replacements
  - Pozzolanic aggregates and Roman Style systems

QUESTIONS?

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