The concrete is a changin’

Kevin MacDonald
Cemstone Products company

InterestingTimes

- We are at the cusp of a materials revolution
- We are (finally) learning to manipulate microstructure
- To explore the potential for the future we need to cast off our illusions

Seeing the future is not so Easy

- In 1876, Western Union decided that telephones would never replace telegram messengers.
- In 1971, AT&T turned down the opportunity to run the Internet as a monopoly.
- In 1980, Ma Bell concluded that cell phones would never replace landlines.

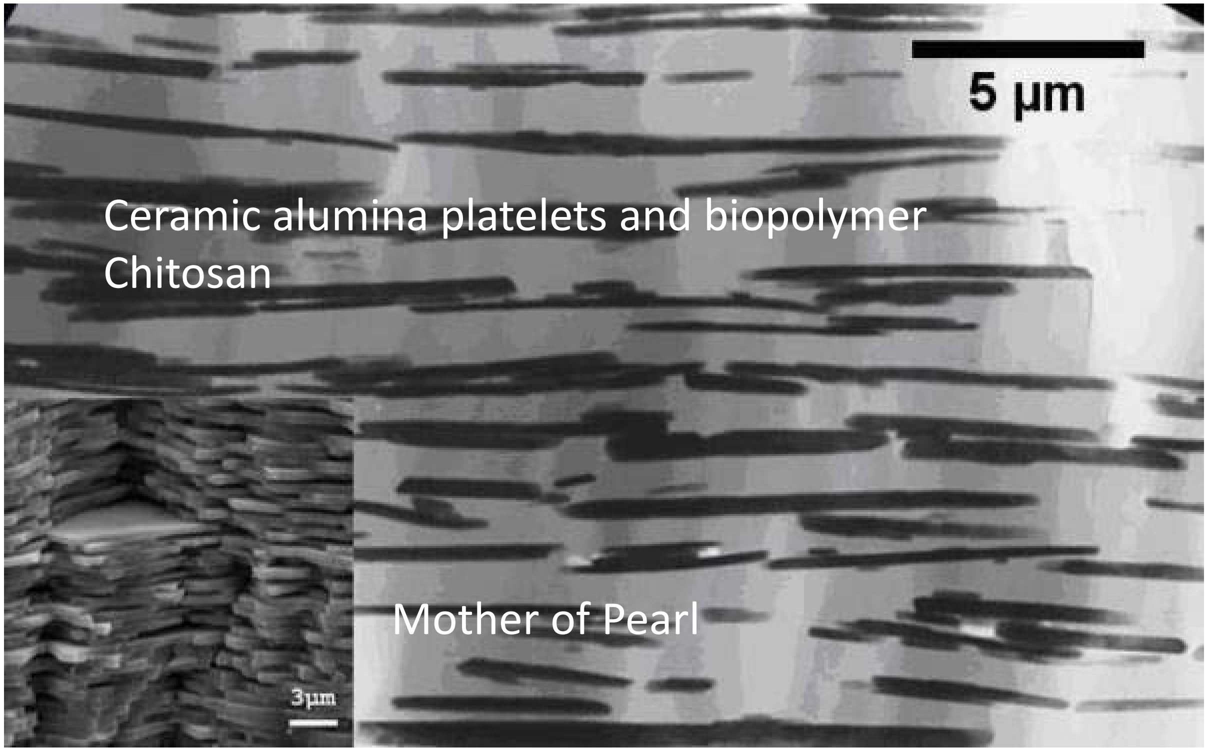
Pity the Poor Clam

- Over many millions of years, nature has devised schemes to combine seemingly incompatible building-blocks —
- 'soft' organic proteins and
- ‘hard' inorganic particles of calcium carbonate — in a manner that produces composite materials with the unusual combination of high strength, hardness and toughness.

Youngs Modulus 250–260 GPa

25 percent elongation at failure

- ETH Zurich (2008, March 10). New Composite Material Is Almost Better Than Mother-of-pearl. *ScienceDaily*.



A History Lesson

- Concrete as we know it is very old material
- Roman and Greek technology included using volcanic materials
- Vitruvius *"There is a species of sand which, naturally, possesses extraordinary qualities….If mixed with lime and rubble, it hardens as well underwater as in ordinary buildings."*

History Lesson

- Romans also used industrial waste”

- Vitruvius “*If to river or sea sand, potshards ground and passed through a sieve, in the proportion of one-third part, be added, the mortar will be the better for use*”

1938 ACI Convention

"Before we can expect findings of research to be adopted and made part of current engineering practice, it is necessary that they be understood, abstracted and molded into a form usable by the practitioner"

Frank T Sheets, President, PCA

Ancient History of the Cement Business

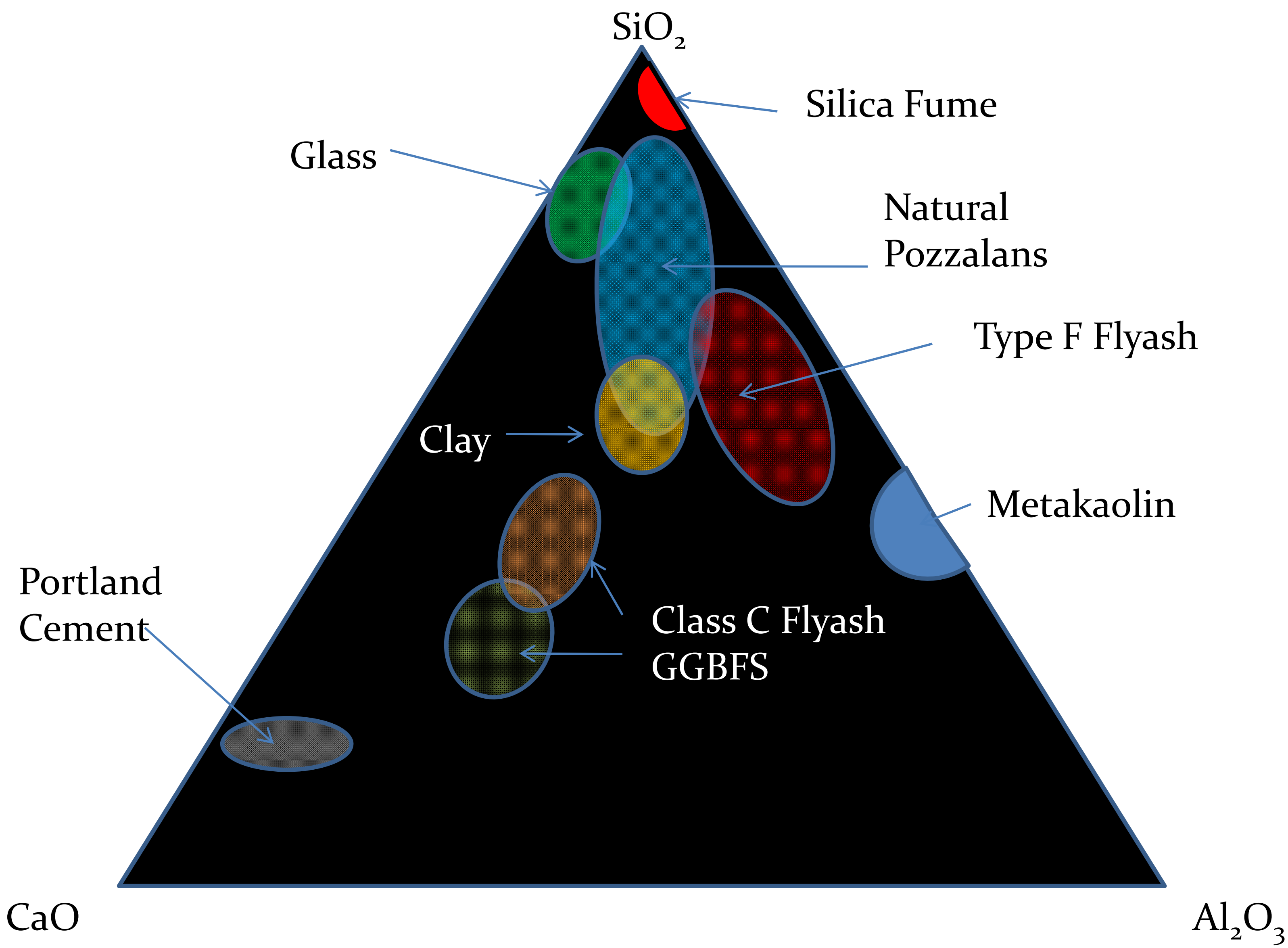
- A good deal older than most people think
- The word “cement” is itself more than 2,000 years old
- Impure limes have been used as cementitious materials even longer
- By 2000 BC the burning of lime in pot kilns was an art
- Roman historians have described the use of Roman cement or hard burn lime in 70 BC
- Romans used kilns and built concrete houses in the first century
- The well know “Pantheon” was an early form of lightweight concrete
- During the middle ages, hydraulic cement was produced in Holland

Roman Concrete – Latin Roots

- Concrescere – to congeal, to grow together, to harden
- Caementum – Crushed Stone
- Pulvis pozzouli – earth from Pozzouli in Italy


The Roman Aqueduct


The Coliseum in Rome



SiO2
Silica Fume
Glass
Natural
Pozzalans
Type F Flyash
Clay
Metakaolin
Portland
Cement
Class C Flyash
GGBFS
CaO
Al2O3

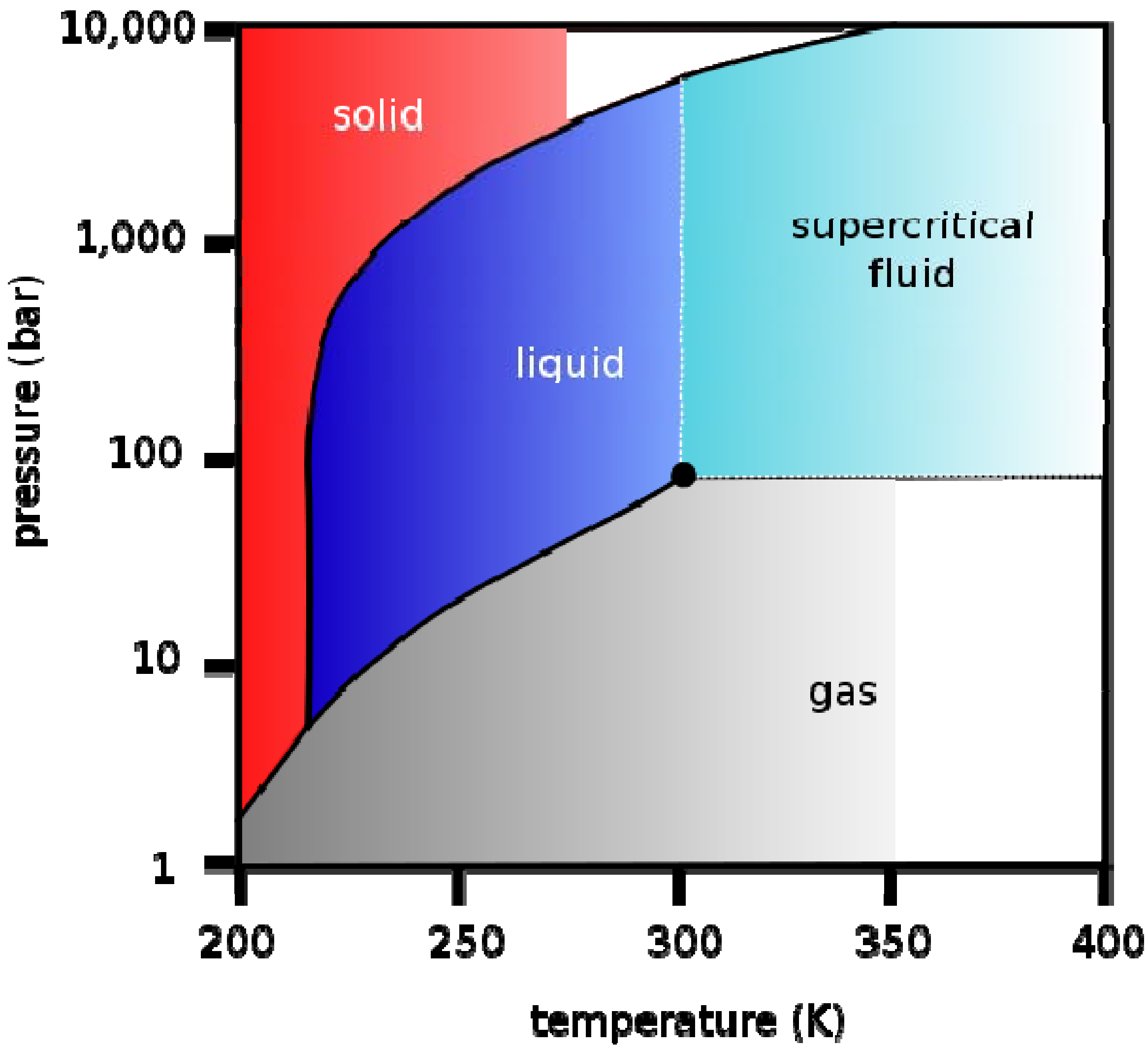
High Performance Materials

Present Factors	TIMESCALE (years)				
	0	5	10	15	20+
Mechanical Properties	Higher com-pressive strength concrete				
	Higher tensile strength, ductile & tougher concrete				
	Improved aggregate/paste bond strength				
	Self curing concrete with porous aggregate				
	More efficient cement hydration				
	Self-Healing microcracks through use of chemistry and microbes				

Present Factors	TIMESCALE (years)				
	0	5	10	15	20+
Volume Change Characteristics	Minimize shrinkage trough paste modification				
	Concrete materials for effective repairs over substrate				
	Concrete that minimizes curling & warping EX: Conductive nanofibers for temperature control				

Sustainable and Safe Materials and Structure

Supercritical CO_2



Present Factors	TIMESCALE (years)				
	0	5	10	15	20+
Environment, Energy, and Safety	Lighter colored concrete for better reflection of heat and light				
	Improved marginal (off-spec) aggregate concrete				
	Low energy cement				
	Recycled cement CO_2 for processing plant of new products				
	High reactivity fly ash through $ScCO_2$ processing and mechano-chemical grinding				
	Nanoparticles, nanotubes, nanofibres for controlling CO_2 , heat of hydration, moisture movements for reduced warping, and electrical conductivity				

Present Factors	TIMESCALE (years)				
	0	5	10	15	20+
	High ASR resistance cement through blending and nanomodification with high reactivity fly ash and $ScCO_2$ processed cement for reduced alkalis				
	Green, economical recycling with nano-processing				

Intelligent Concrete Materials

Present Factors	TIMESCALE (years) 0	5	10	15	20+
Nanotechnology-Based Sensing Technologies	Sensors for recording loading in pavements and bridges				
	Sensors for recording joint deterioration				
	Nano-Graphite fibers for strain measurements				
	Chemical sensors for early warning of ASR, corrosion, and sulfate attack				
	Viscosity measurements in-situ during construction/paving				
	Flexible, self-powered sensors in concrete				
	Effective communications sys-tems for concrete				
	Nano-Sensors for monitoring concrete from very early age				
	Monitor concrete in bridges and pavements				

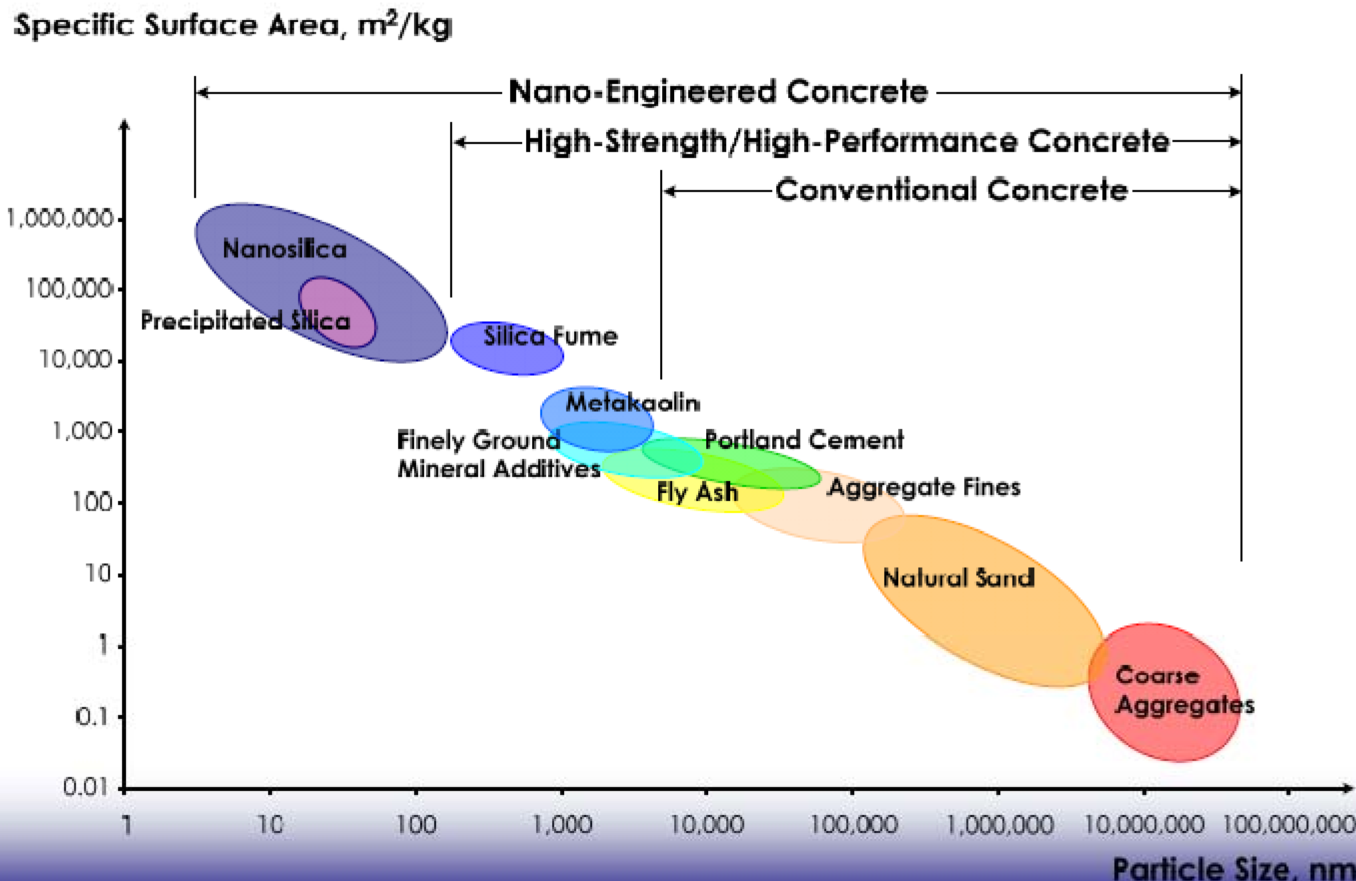
Novel Concrete Materials

Present Factors	TIMESCALE (years)				
	0	5	10	15	20+
Nanotechnology-Based Processing	Self-compacting concrete				
	Self-consoli-dating concrete for slip-cast paving				
	Extrusion processing for specialty products and armor protection				
	Functionalized nano-particles for control of rheological properties during construction				
	Functionalized cement for improved mechanical properties				

Fundamental Multi-Scale Model for Concrete

Present	TIMESCALE (years) 0	5	10	15	20+
Characterization and Modeling	Development of scale links between nano-scale model and microstructural model				
	Characterization of the hydration process				
	Characterization of aggregate-cement paste chemical inter-action				
	Nano-scale model of Portland cement concrete				

PARTICLE SIZE SCALE RELATED TO CONCRETE

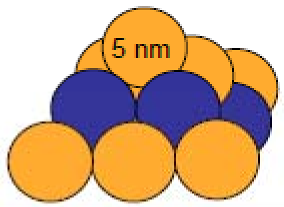


What do Concrete and Oranges have in common?

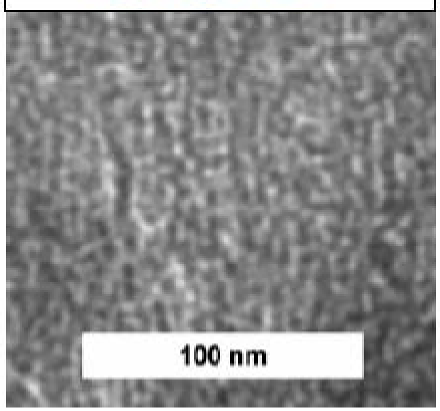
*The Nano-Granular Nature of C-S-H**

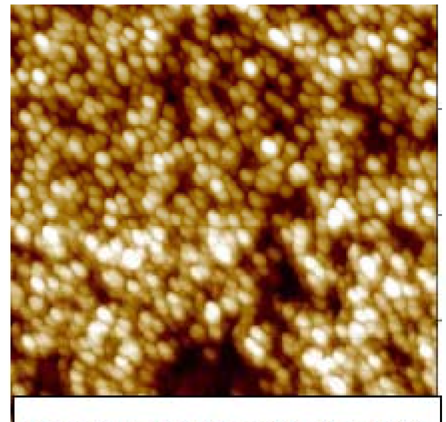
- HD C-S-H
- LD C-S-H

Spherical Limit Packing
Density = 0.74
No. of contact = 12/ sphere

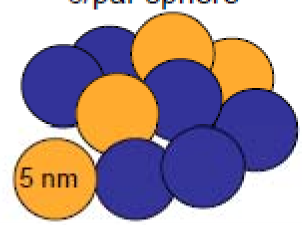


Nature, 1998





Random Packing Limit = 0.64
No. of contact (mean)
= 6/par sphere



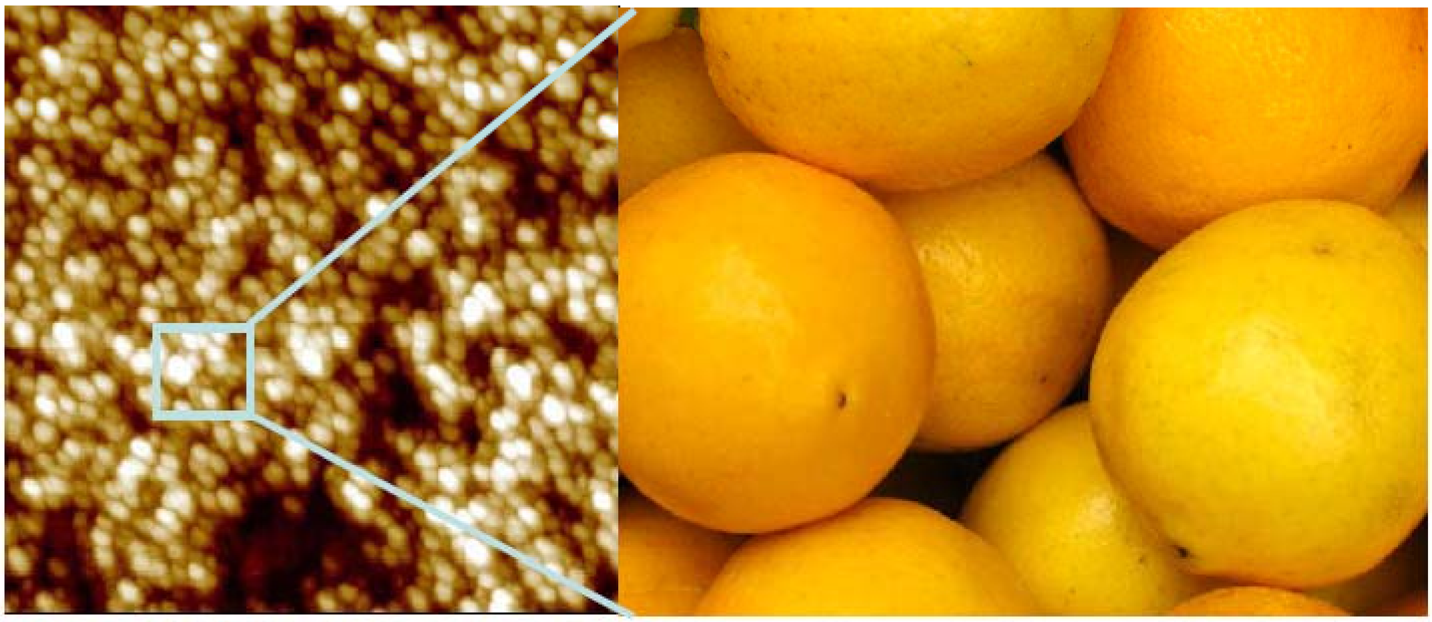
Science, 2004

(*) Constantinides, G., Ulm, F.-J., (2007). The nanogranular nature of C-S-H, JMPS, January 2007

Picture Credit: Richardson, 2004; Nonat 2004

*The Nano-Granular Nature of C-S-H**

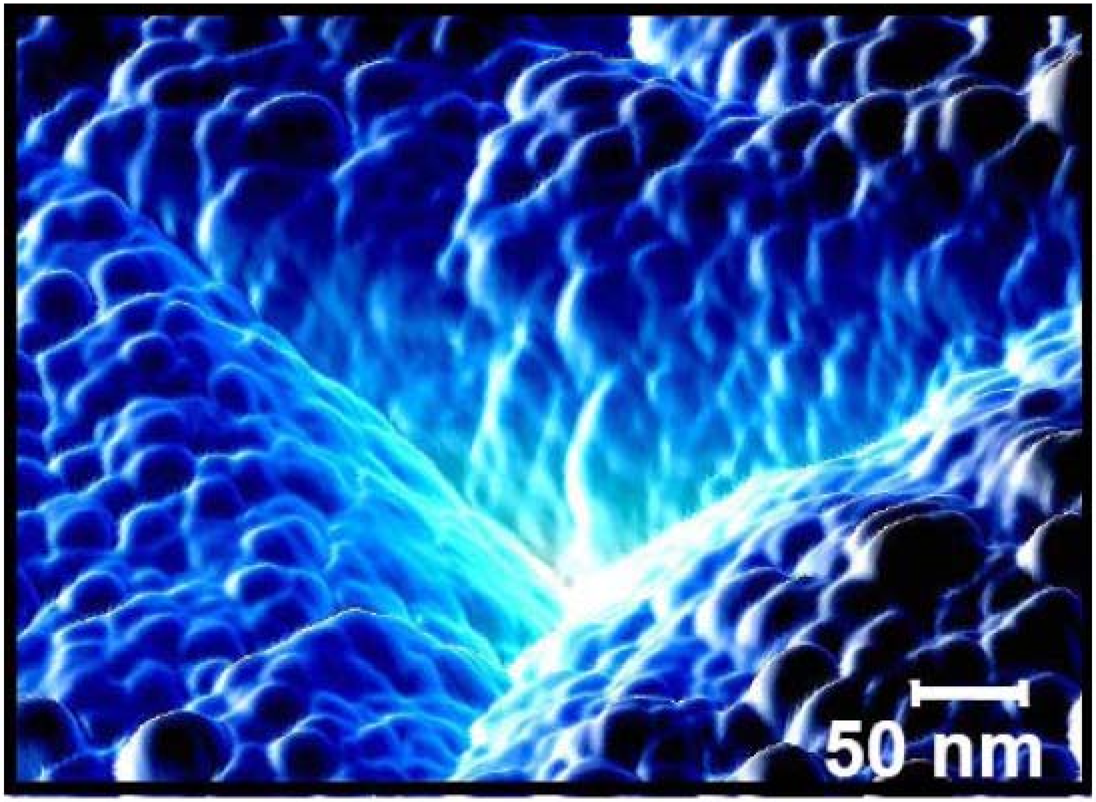
- What concrete and Oranges have in Common?



(AFM – Image: C-S-H Nanoparticles
From Nonat, 2004)

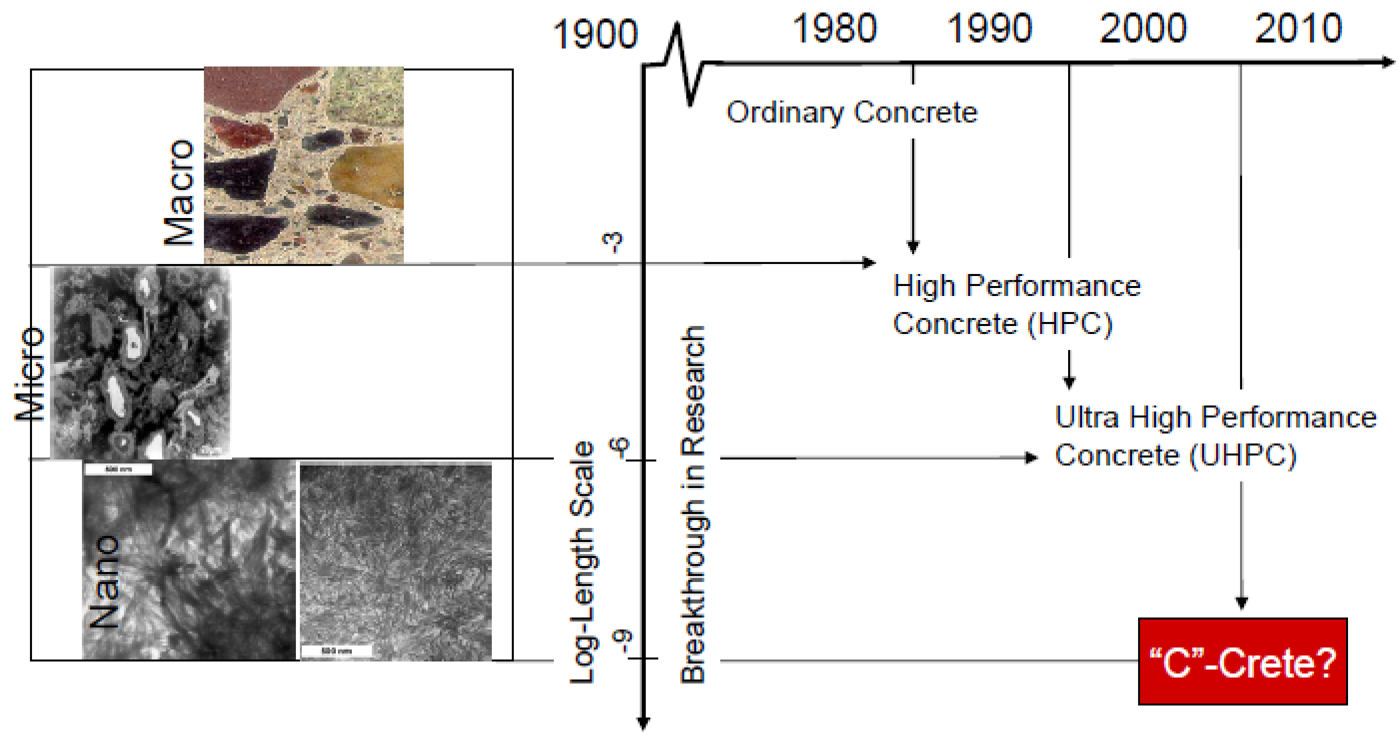
(*) Constantinides, G., Ulm, F.-J., (2007). The nanogranular nature of C-S-H, JMPS, January 2007

*The Nano-Granular Nature of Bone**



(*) Tai, K., Ulm, F.-J., Ortiz, C. (2006). "Nanogranular origins of the strength of bone", NanoLetters.

Progress on the Concrete Front



SUSTAINABILITY

Definition/ VALUE

- Use Less
- Higher functionality
- Last Longer
- Lower Maintenance
- Less ‘Loss of Use’

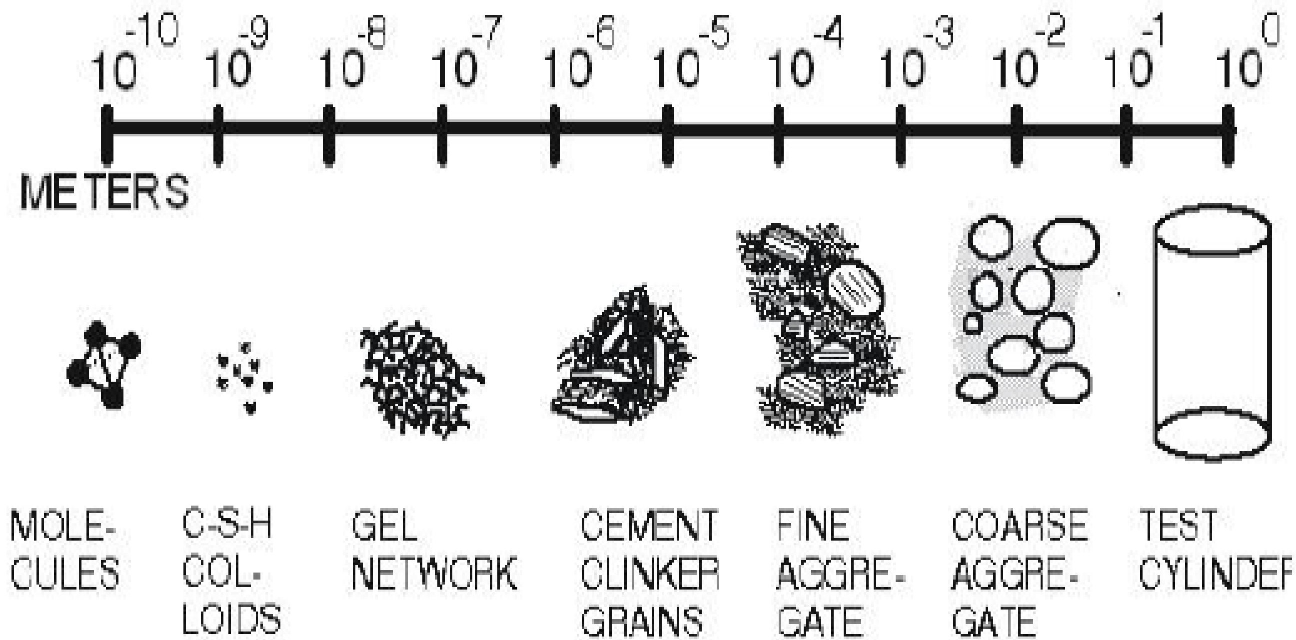
Characteristics

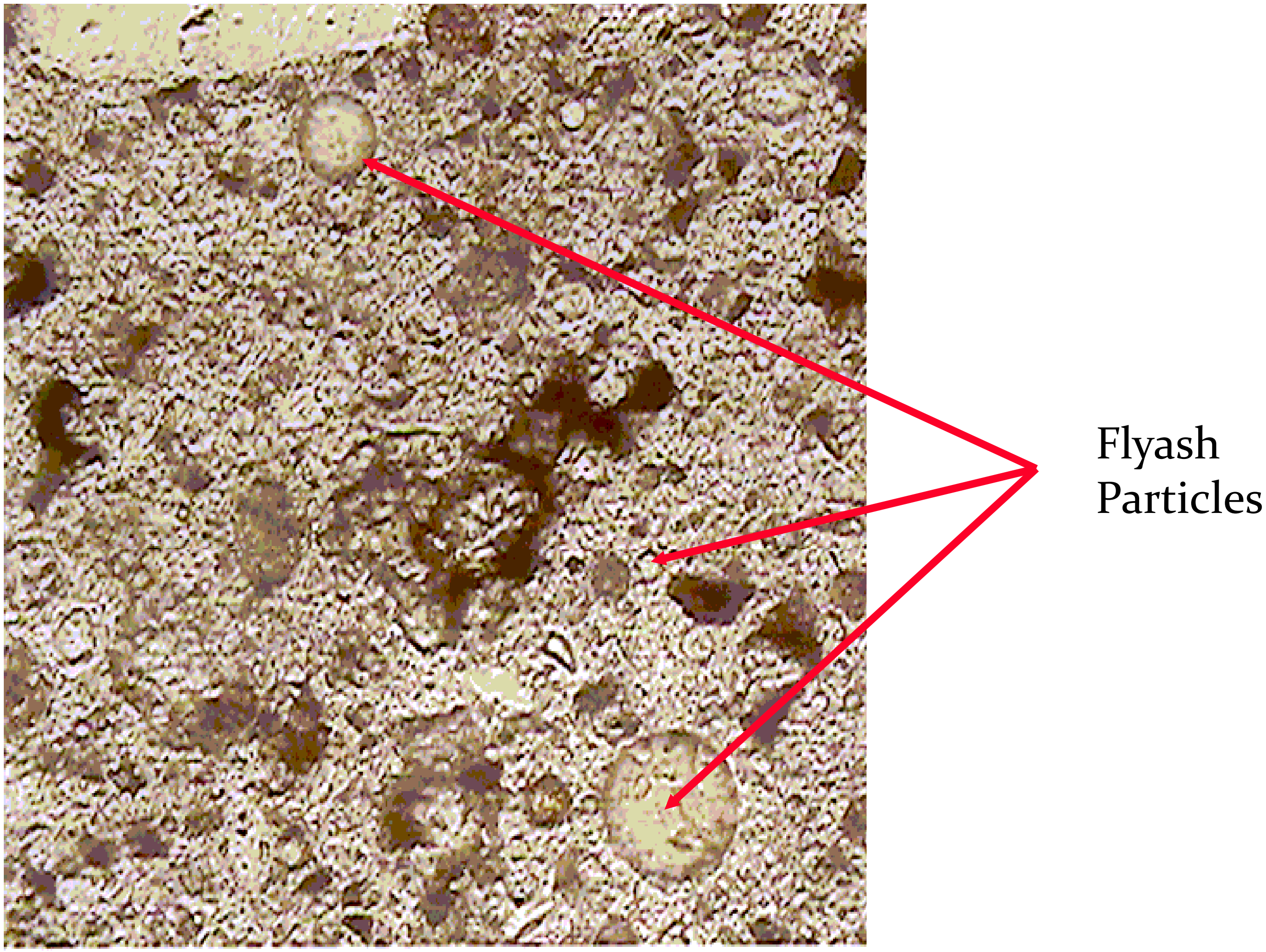
- Higher Strengths
- Improved ductility
- Improved durability
- Improved recyclability

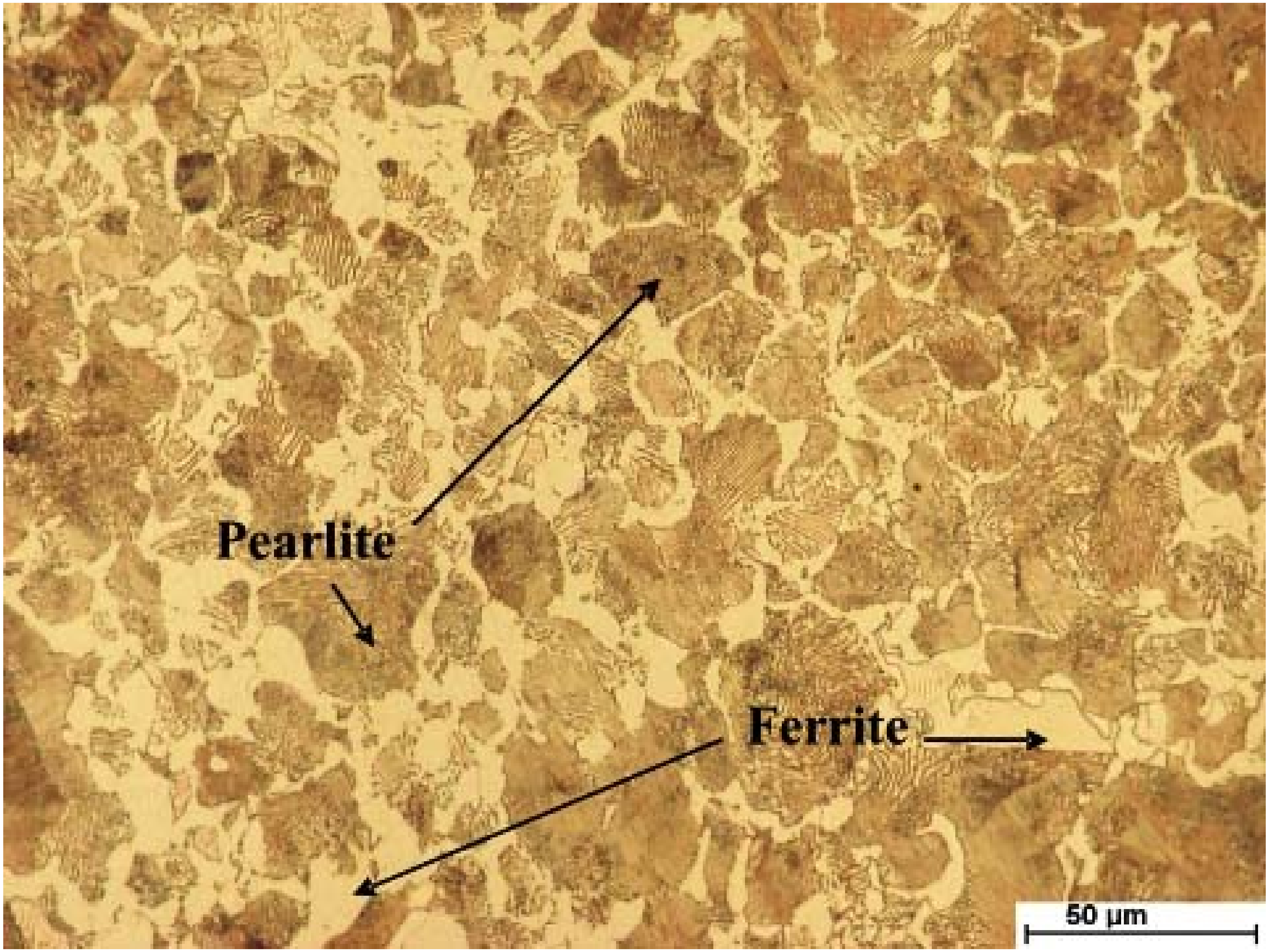
Mechanical Properties

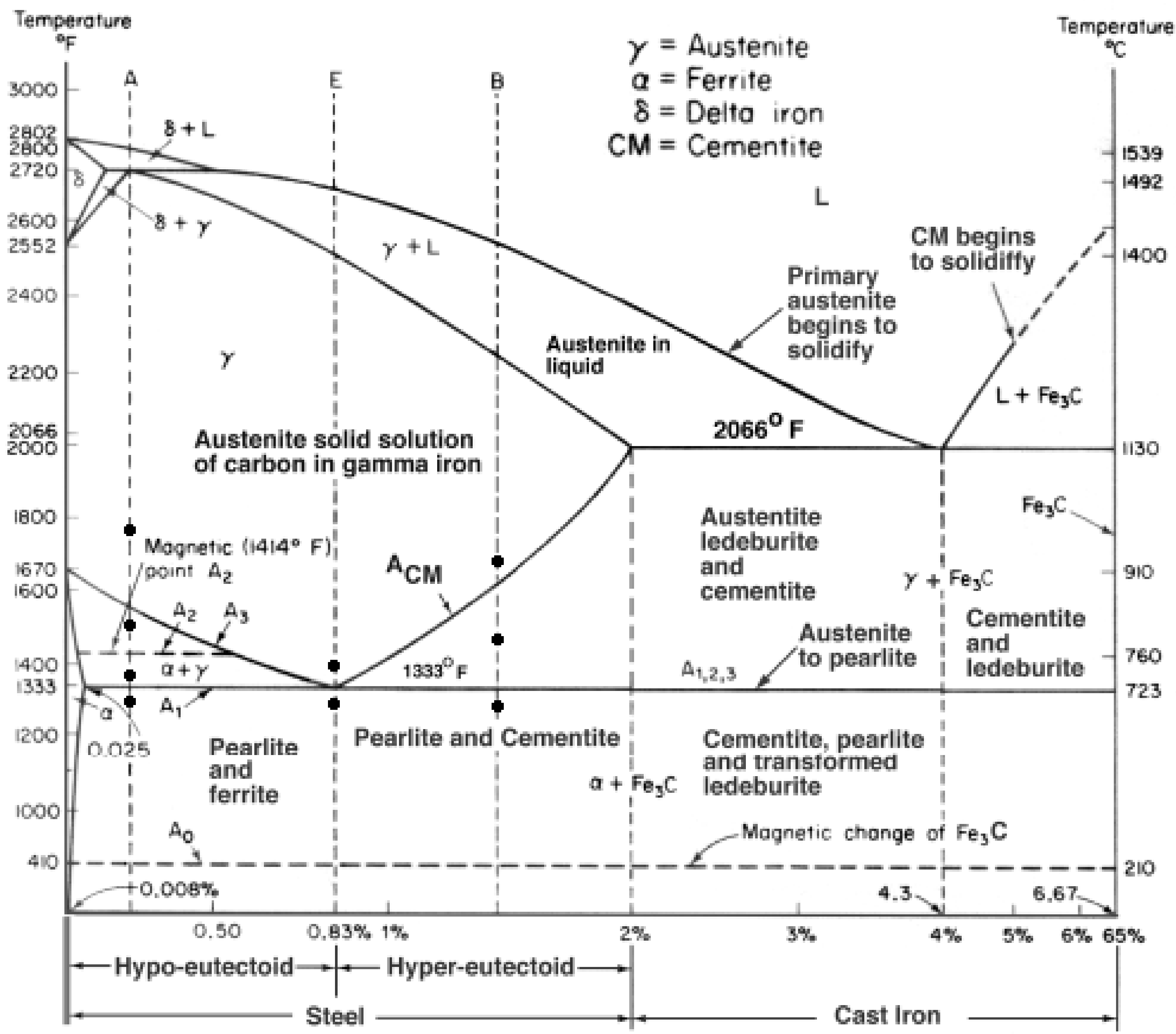
- Compressive strength
- Flexural strength
- Shear strength
- Ductility/toughness
- Impermeability
- F/T
- Abrasion
- E-Modulus

Concrete Microstructure




Flyash
Particles

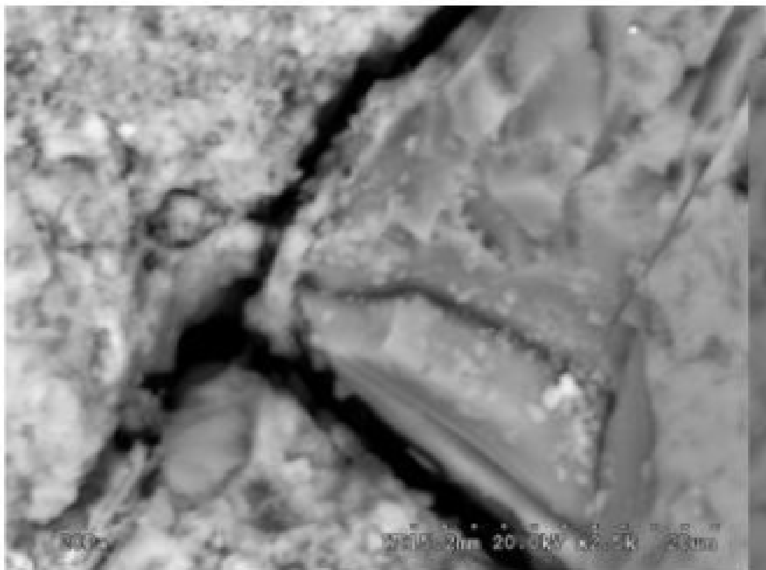

Pearlite
Ferrite
50 µm



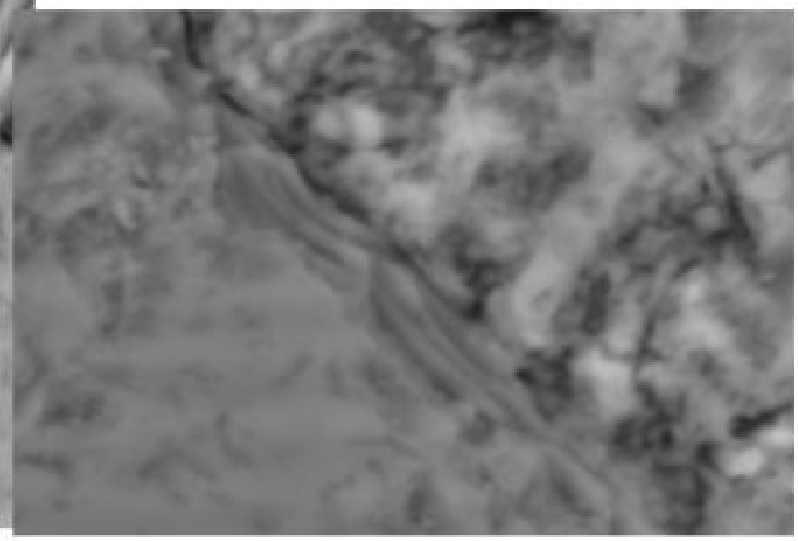
Temperature °F
Temperature °C
γ = Austenite
α = Ferrite
δ = Delta iron
CM = Cementite
A
E
B
3000
2802
2800
2720
2600
2552
2400
2200
2066
2000
1800
1670
1600
1400
1333
1200
1000
410
1539
1492
1400
1130
910
760
723
210
δ + L
δ
δ + γ
L
γ + L
γ
CM begins to solidiffy
Primary austenite begins to solidify
Austenite in liquid
L + Fe3C
2066° F
Austenite solid solution of carbon in gamma iron
Austentite ledeburite and cementite
Fe3C
Magnetic (1414° F) point A2
ACM
γ + Fe3C
A2
A3
Austenite to pearlite
Cementite and ledeburite
α + γ
1333° F
A1,2,3
A1
α
0.025
Pearlite and ferrite
Pearlite and Cementite
Cementite, pearlite and transformed ledeburite
α + Fe3C
A0
Magnetic change of Fe3C
0.008%
4.3
6.67
0.50
0.83%
1%
2%
3%
4%
5%
6%
6.5%
Hypo-eutectoid
Hyper-eutectoid
Steel
Cast Iron

Optimized Microstructure – Concrete Interfacial Transition Zone (ITZ)

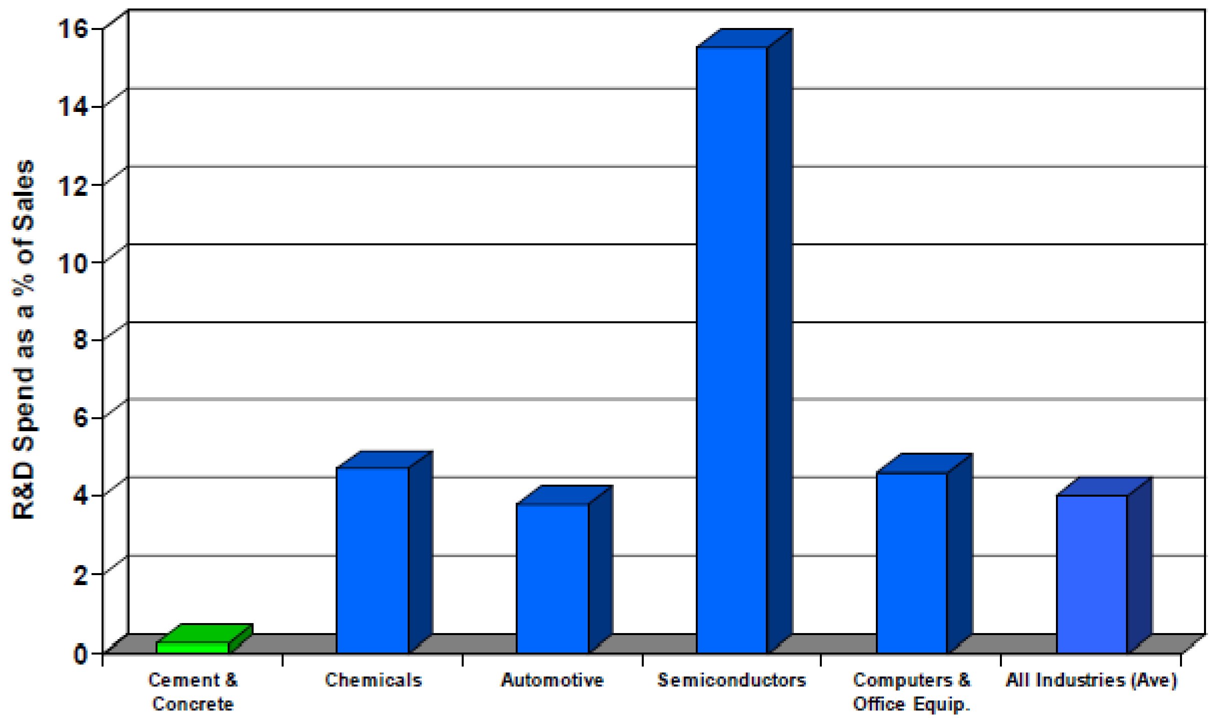
Normal Concrete ITZ at 2500X Magnification



Nanomodified Concrete ITZ (2% Clay/2 % Polymer at 3500X Magnification



R&D $'s - Small Numbers!



Little funding for construction research!

Concrete - Material of Choice for Construction

Advantage

- Availability
- Affordability
- Unrestricted geometries
- Durability
- Environmental friendliness

Opportunities

- Cost
- High Labor
- Density (Weight!)
- Low ductility, weak in tension (Brittle!)
- Durability (Cracking!)
- Environmental load (CO_2)

Drivers for Change

Initial costs

- Materials (Cement, Aggregates, Water)
- Labor & Time of construction
- Energy (cement)

Total cost of ownership - Durability

- Repair, restoration, renovation
- Maintenance

Environmental load - Environmental pressures and regulations

- CO_2 reduction
- Declining quality of raw materials
  - Cement
  - Aggregates

Drivers for Change - Initial Costs

Materials

	%
Concrete	31
Forms	8
R-bars	7
	45

Labor

	%
Placement & Finishing	16
Form works	27
R-bars placement	11
	55

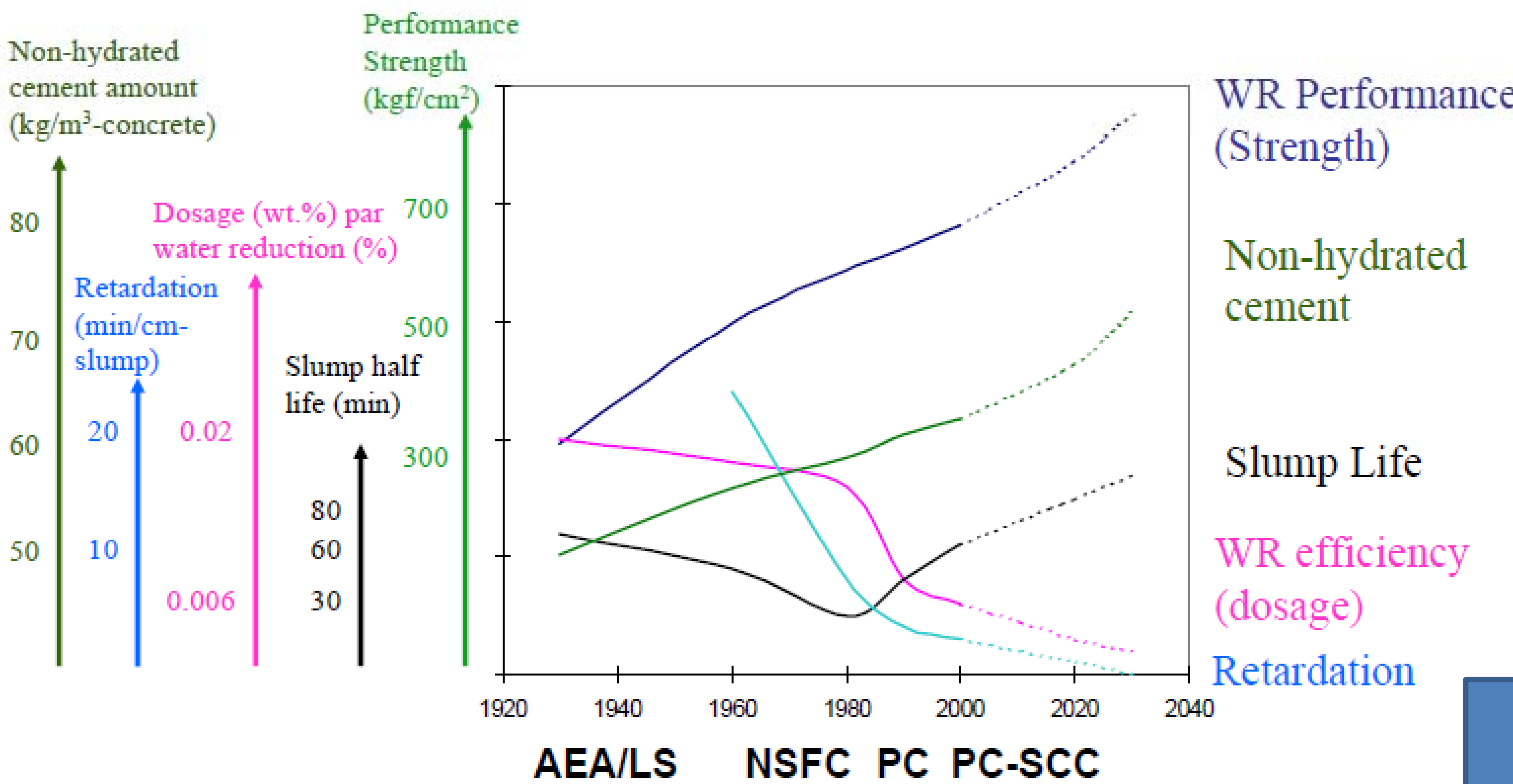
Labor - Challenges

Concrete flow properties (simplify placing and finishing operations)

Curing/Finishing (reduce labor and improve quality (durability and appearance) of concrete after casting/placement)

Reinforcing steel (tough concrete - saving on rebar labor, simplifying placing and reduce environmental load (steel))

Concrete Placement Technology - Challenges

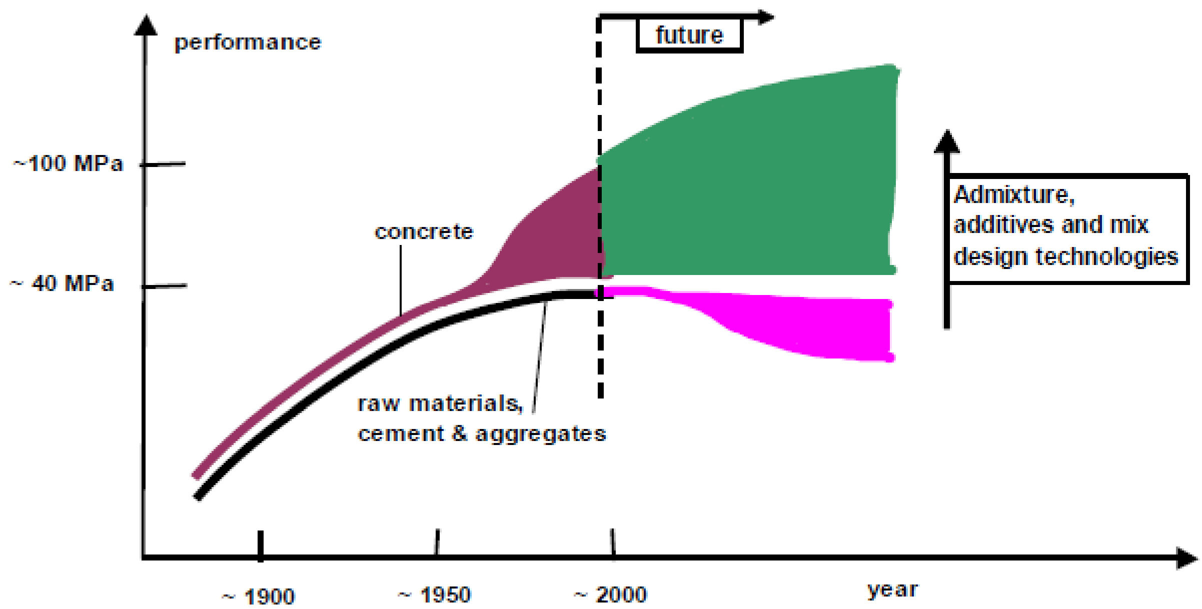


Raw Materials

Enabling the use of challenging raw materials for normal and high performance concrete

- **Cement**: blended cement
- **Aggregates**: fines, marginal aggregates
- **Water**: water management (recycled water)

Raw Materials



Cement – Challenges Energy and CO_2

Use of secondary fuels

- Six-fold increase in the last ten years

Increased use of SCM's (CO_2!!!)

- EU 11%, AP 34%, Russia 55%, NA 2% - to stay at 0 level of CO_2 emission increase

Limestone blended cements (6-35%)

Cement – CO_2!!!

Possible Solutions

Clinkers with less CO_2 emissions

BCASF (belite,calcium sulfoaluminate and calcium alumino-ferrite)

- Emits 25% less CO_2 than OPC
- Raw materials readily available everywhere

CO_2 sequestration

- Economics!

Aggregates - Challenges

Declining availability of quality aggregates

-growing problem around the world-

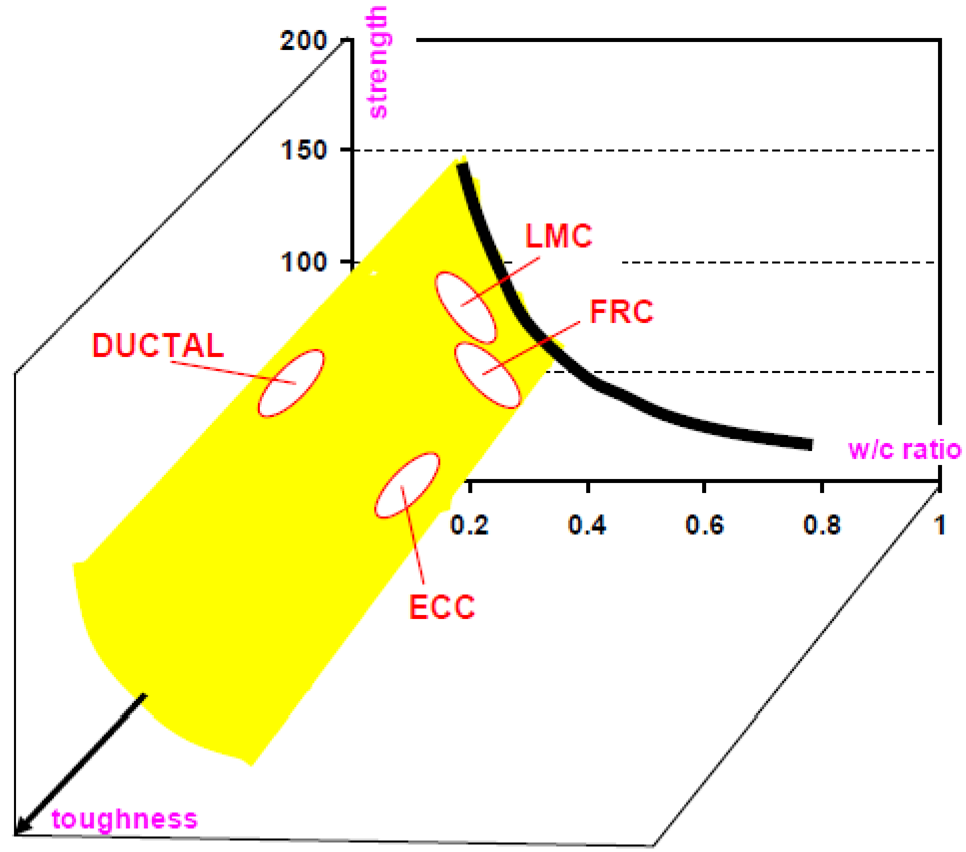
Development of technologies to enable the use of marginal (clay, fines) aggregates

Total Cost of Ownership - Durability

Problem	Solution strategies
Brittleness - cracking	Improve ductility
Dimensional stability	Reduce shrinkage
▪ Thermal and hydral	▪ Improve curing (self-curing)
Permeability	Reduce permeability
▪ ASR & DEF	▪ Integral waterproofing
▪ Sulfate attack	▪ QC of raw materials
▪ Corrosion	▪ Self repair/sealing
▪ Freeze/thaw	▪ Admixtures
Estimating life-expectancy	Self monitoring

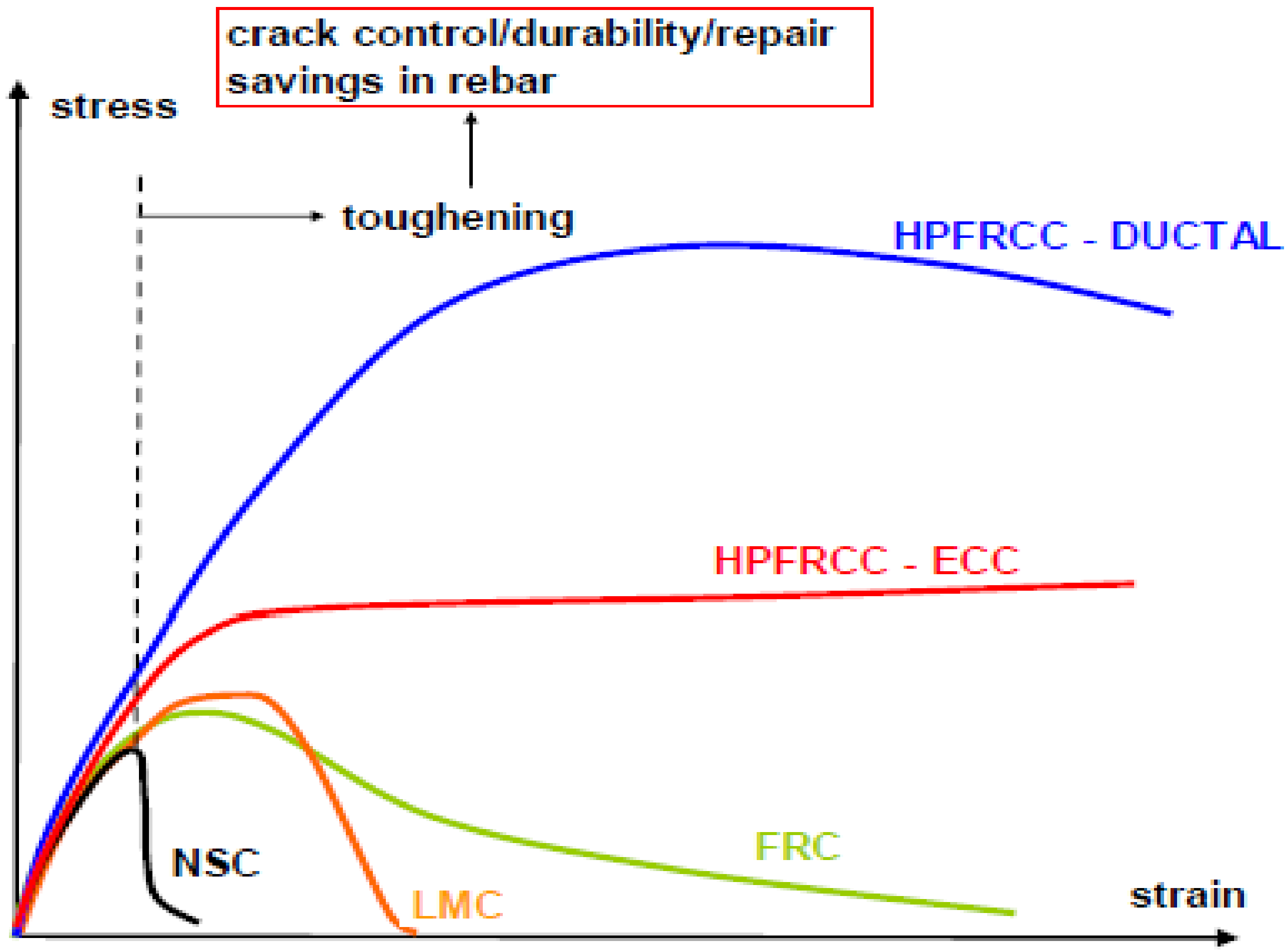
Water transport: Root-Cause of the concrete durability problem

Durability & Ductile Concrete



Durability & FRC

New generations of fibers will transform concrete from a strain-softening



Durability & FRC

Building code will adapt advanced modeling tools to design with ductile concrete

- Seismic improvement
- Reduction of conventional reinforcement
- Thinner sections
- Crack control and prevention
- Durability

Curing

In US less then 25% of concrete is cured according to standards

Lack of standard methods to verify curing adequacy

Labor intensive, time consuming

Curing in the field is critically important to the durability of concrete

Curing - Directions To Go

Address:

- Evaporation – environmental conditions
- Self-desiccation – low w/c concretes
- Labor intensive process delaying construction cycle
- Performance standards for curing in the field

Concrete & Esthetics

Dramatic improvement in the esthetic appeal of concrete

- Self cleaning concrete TiO_2 (Ital Cementi)
- Transparent concrete (LiTraCon)
- Image printing (Grace)

Future - Interactive/Smart Concrete

QC – (e.g., monitoring of w/c in place)

- Electronic & chemical sensors
- In-place non destructive testing

Self repair

- Triggered inorganic reactions
- Triggered organic/biological reactions

Future

- Ductile, flexible, breathable, permeable or impermeable. Properties on-demand
- Dial-in set, strength, permeability, etc
- Engineered materials: Maximize what you have locally, avoid un-necessary transport
- Immune to freeze-thaw, corrosion, sulfate and other environmental attacks
- Specialty: (blast resistant, conductive…)

………………………………

Barriers and Issues

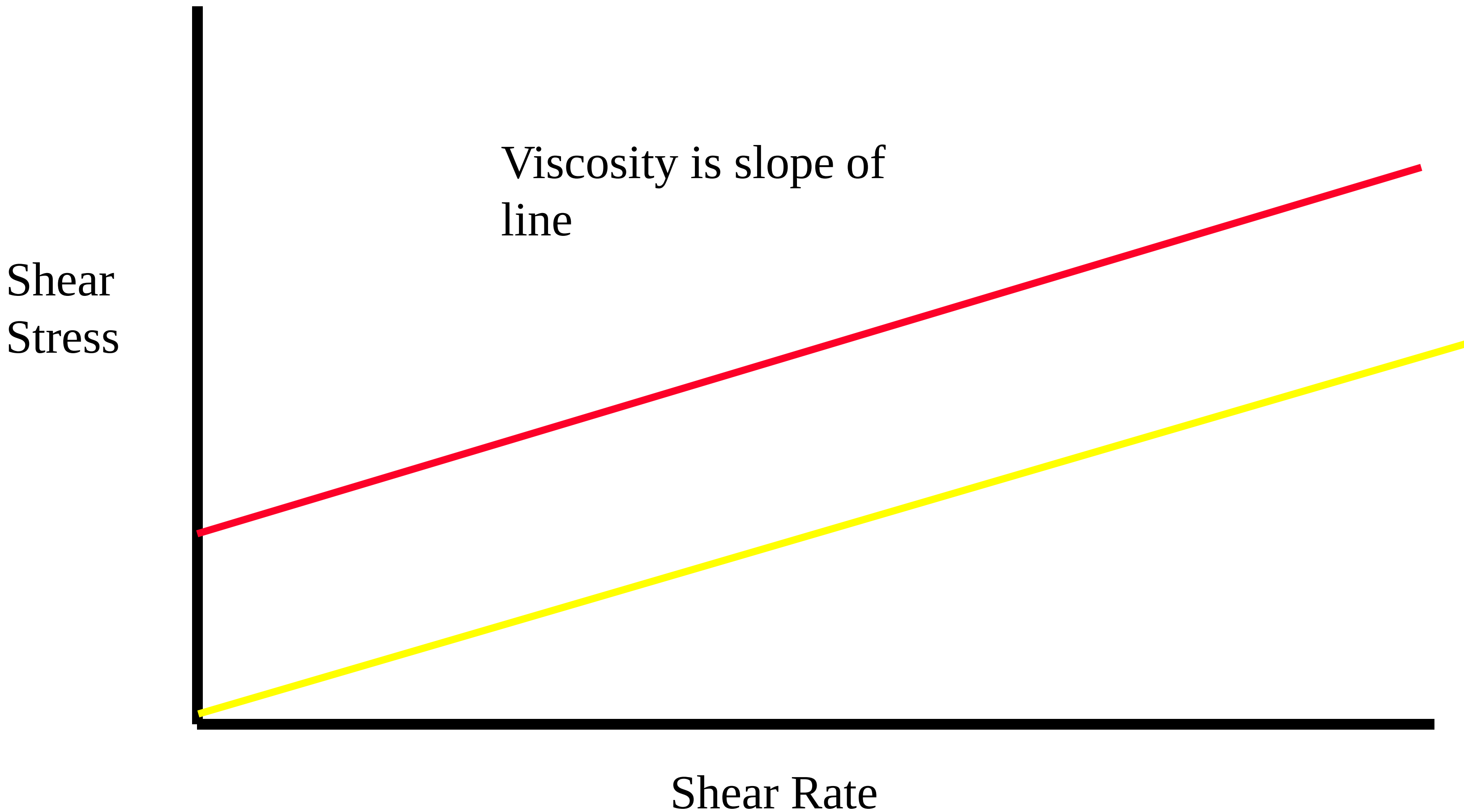
- Lack of adequate R&D funding
- Slow adoption rates of new technologies
- Low level of collaboration for multidisciplinary problems
- Prescriptive vs. performance based standards
- Low level of QC technologies
- Lip service to life-time costs
- *Poor image of cement–based materials !!!*
- ....

Mixture Proportioning and Adjustment

Fluid Properties the Basics

- Newtonian Fluids have a viscosity that relates shear rate in the fluid and shear stress in the fluid

Newtonian and Bingham Model

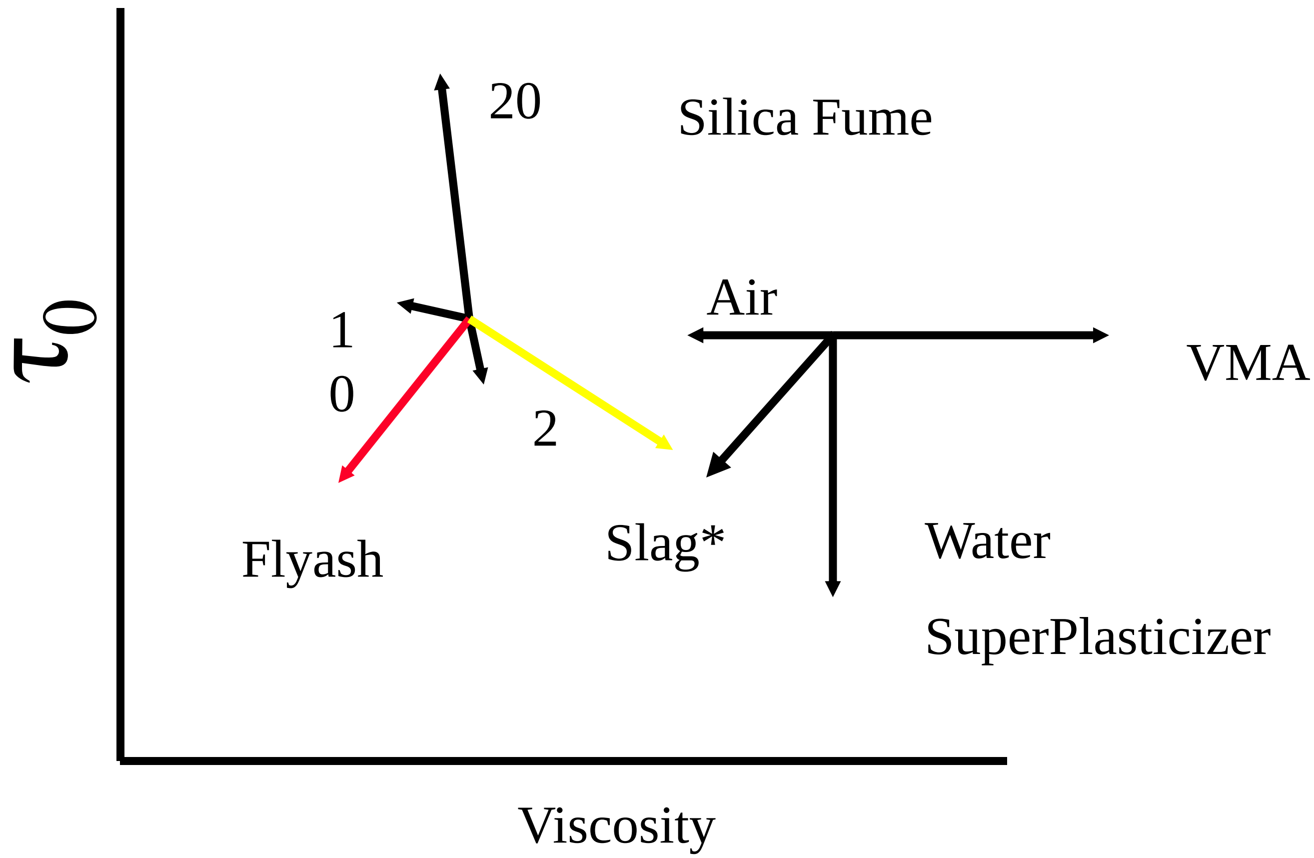


Viscosity Models

Bingham
Plastic

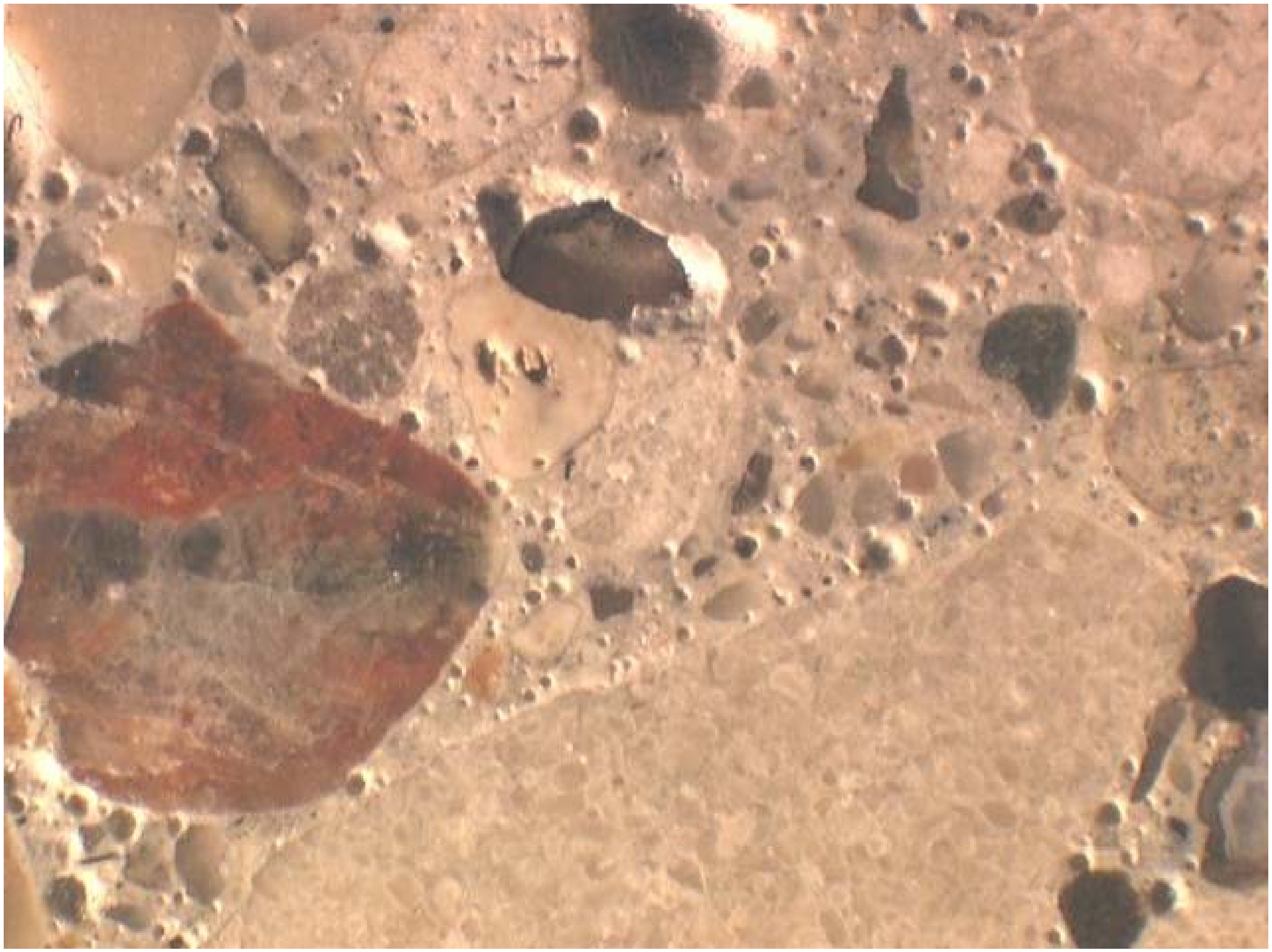
$$\tau = \tau_0 + \mu \dot{\gamma}$$

Mixture Design - Rheology

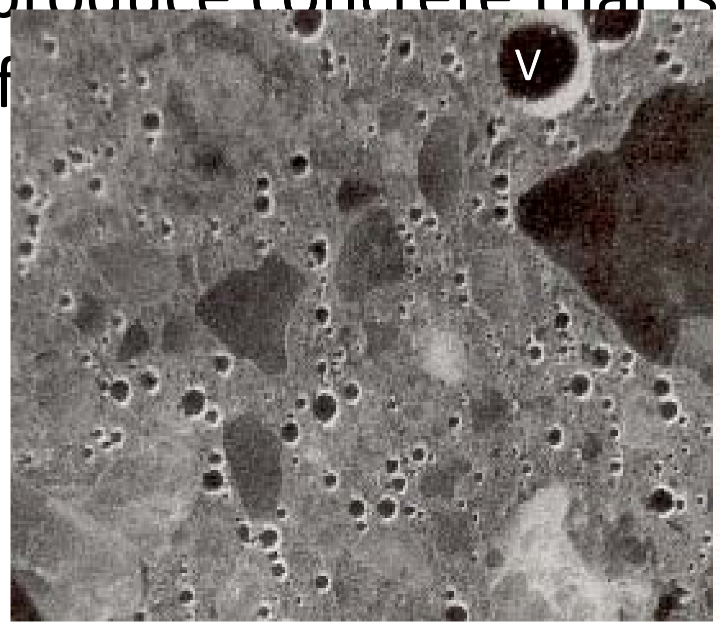


Slump is not a good indicator of strength

Proper air content is critical



Air-Entraining Admixtures

- Definition
  – Are used to produce concrete that is resistant to the effects of 

nd to improve workability

Polished section of air-entrained concrete as seen through a microscopic

High Performance Materials

- Higher strength
- Greater durability
- Increased speed of construction
- Reduced environmental impact

In the coming decade

- Concrete will be more complex
- Prescription specifications will diminish
- Better materials characterization
- Better Microstructure models may lead to new materials
- New Design methods could be introduced

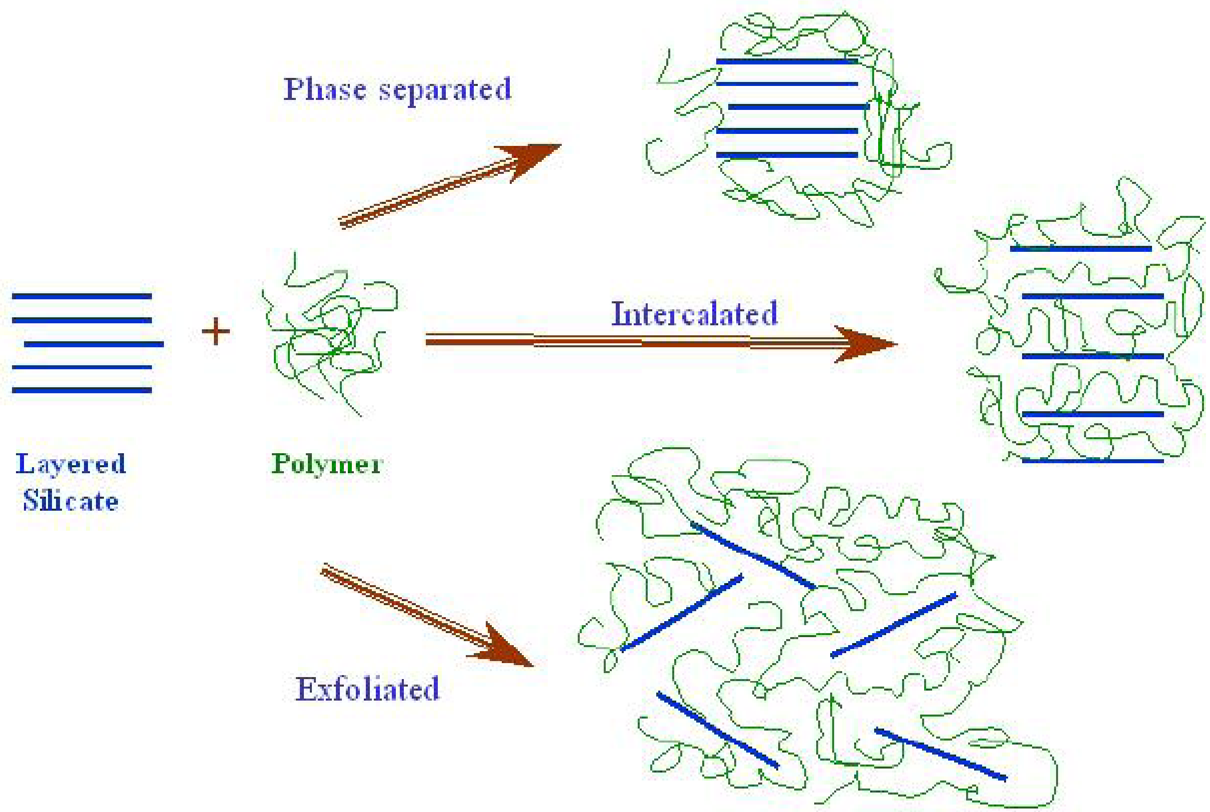
Cement Design

- More Boutique materials
- More and more complicated plants
- More efficient use of cement – too much micro fine aggregate is wasted

Changes can coming quickly

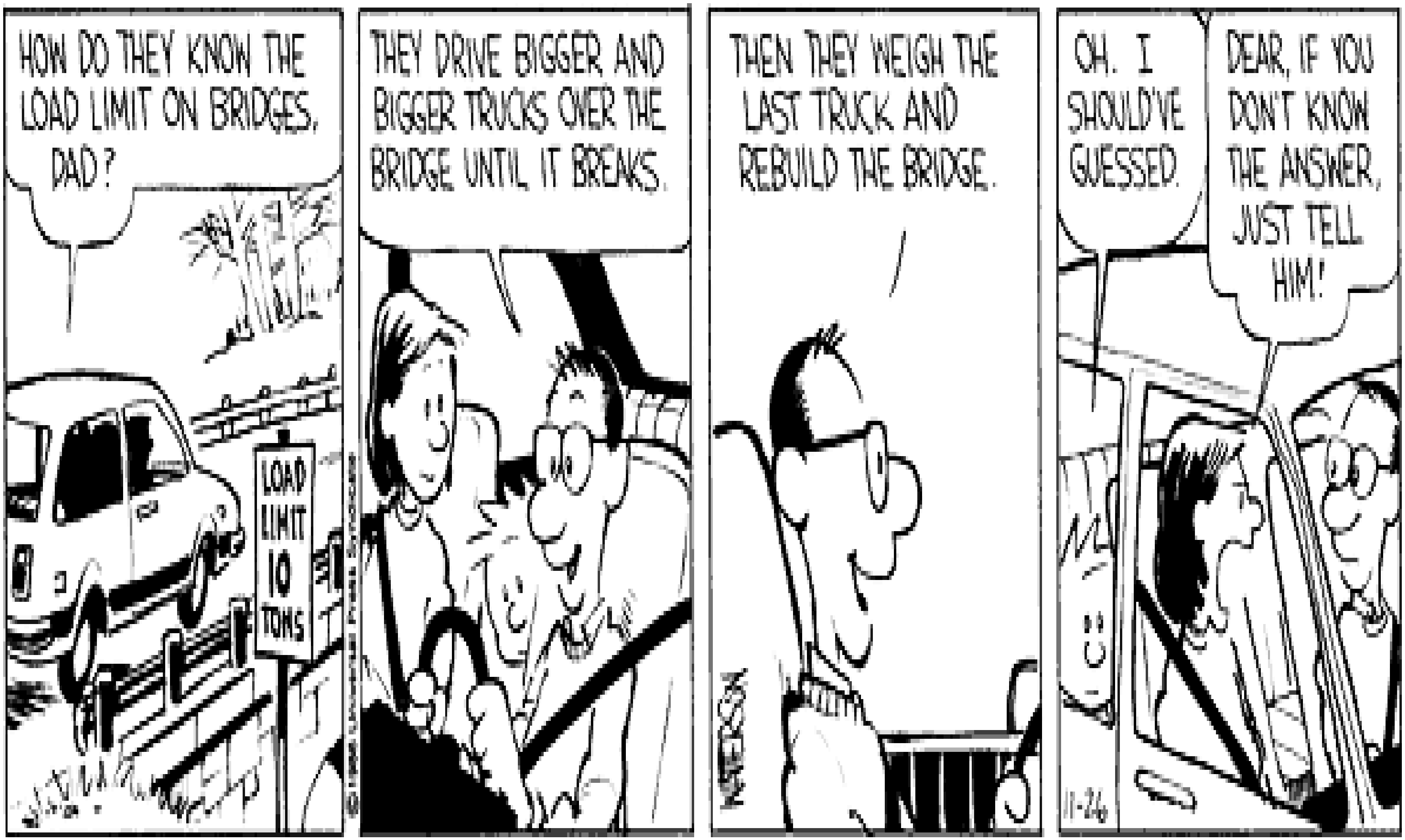
- Sacks will go away –
- Slump cones will be relegated to the dustbin of history
- Perhaps even our idea of concrete will change

Clay Nanocomposites

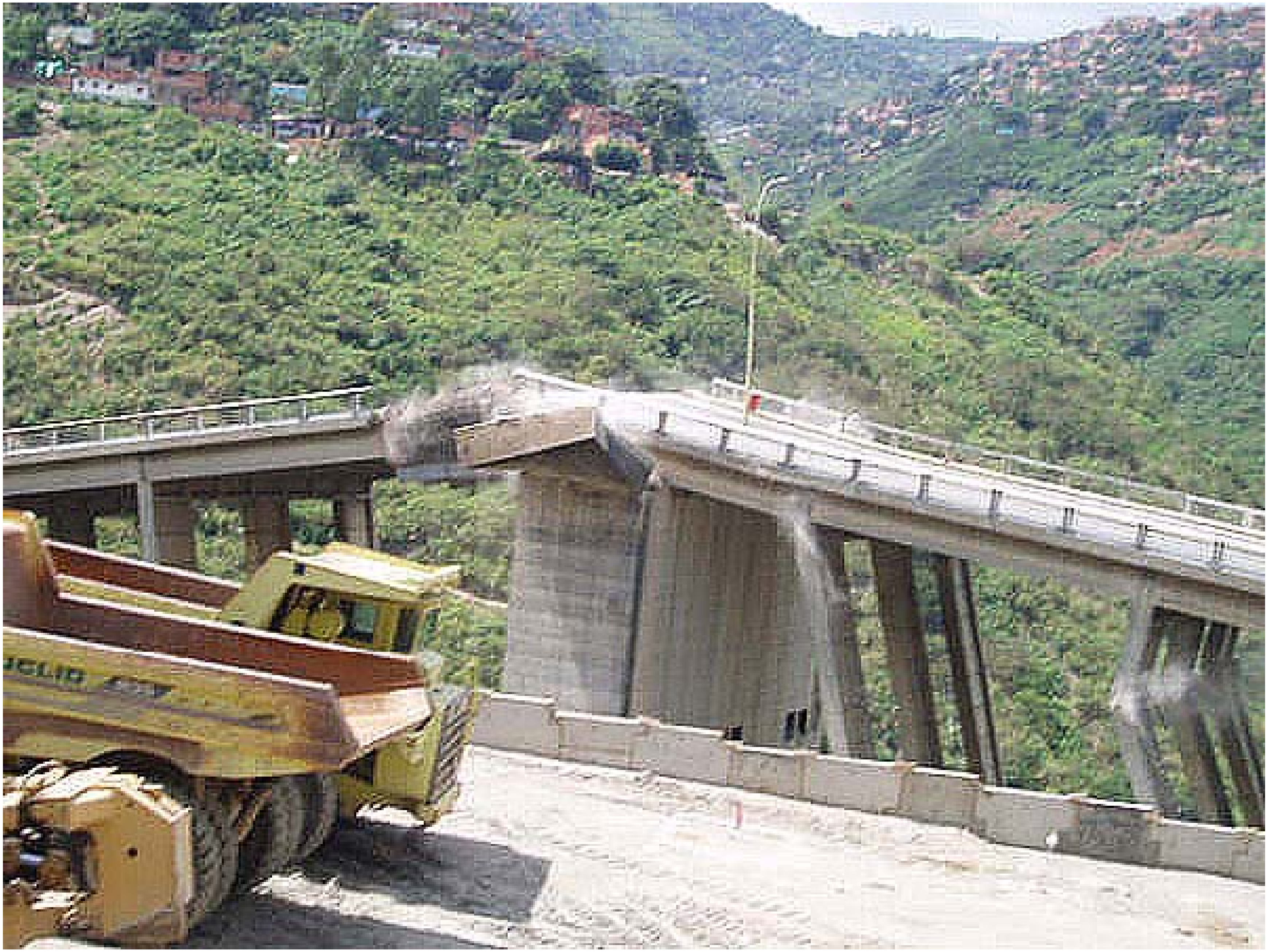


Structural Design

- Methods will be changing as materials science methods develop


HOW DO THEY KNOW THE LOAD LIMIT ON BRIDGES, DAD?
LOAD LIMIT 10 TONS
THEY DRIVE BIGGER AND BIGGER TRUCKS OVER THE BRIDGE UNTIL IT BREAKS.
THEN THEY WEIGH THE LAST TRUCK AND REBUILD THE BRIDGE.
WATTERSON
OH. I SHOULD'VE GUESSED.
DEAR, IF YOU DON'T KNOW THE ANSWER, JUST TELL HIM!
11-26

COLLAPSE...

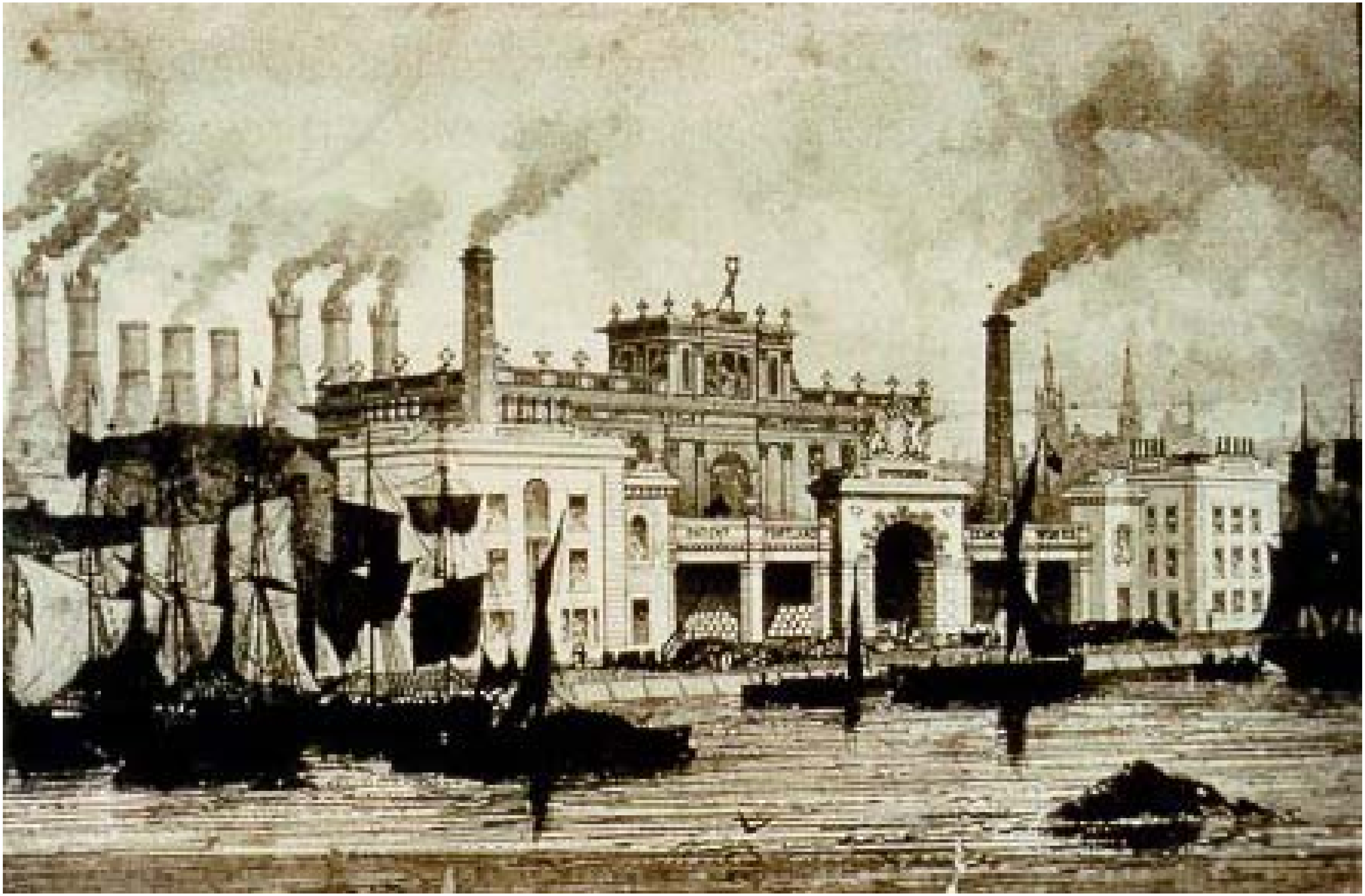


Design Methods

- Plasticity analysis
- Particulate composite and Fibre Composite Methods
  - Rule of Mixtures
  - Griffith Theory

Reinforcement

- Stainless Steel
- Steel Fibres
- Steel Whiskers
- Low Modulus Materials - ductility



Specification and Concrete Requirements

- Section 3300 and Notes
- Strength
- W/C ratio
- Material Properties
- Minimum Quantities

Unwritten Owner Requirements

- Shrinkage
- Curling
- Cracking
- Appearance
- Longevity

Constructor Requirements

- Workability
- Finishability
- Setting Characteristics
- Strength Gain for Stripping and Stressing
- Cold and Hot Weather

Prescription Specification

- 4000 psi at 28 days
- 0.40 w/c ratio
- 550 lb type I cement
- Coarse Aggregate 60 percent of aggregate volume

Why Performance?

- Rate of Change in Concrete industry too fast for designers to keep up with
- Material Science replacing old methods of study of concrete – not reflected in industry

Case Study for Spicy Concrete

- Design a structure to have a service life of 100 years

Four Common Approaches to Concrete Material Durability

- "Ostrich Syndrome" – acknowledges the non-existence of any durability problem.

- "Comfort Zone" – the solutions exist by improvements (tweaking) with the current materials.

- "Test-Until-You-Drop" – relies on endless test data developed internally or regionally.

- "Durability Models" – relies on numerical scientific modeling. Relies on proper numerical relationships and input parameters.

Significant Obstacles

- Many tests are very harsh – otherwise good performing concrete will fail the tests
  - I.e C1293
- Tests are time consuming and curing sensitive
- Bad for a batchwise process like concrete

Modeling Durability

- Diffusion and Convection
- Materials Service Life – FHWA, USACE
- ACI 365
- Predict influx of chlorides, sulphates, etc.
- Rely on permeability and diffusion (transport) in solid bodies

Conclusions

- A microstructure-based model will change technology dramatically
- Complexity will increase as we better understand the small end of the dimensional spectrum
- Change will occur – you need to try to keep up.