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COLLEGE OF ENGINEERING | School of Civil and Construction Engineering

The Influence of Slag on Reducing Concrete Pavement Joint Deterioration

Jason Weiss and Burkan Isgor

Oregon State University

October 26th, 2020; 7:00-8:00 AM

Description of the Talk

Presenter: Jason Weiss and Burkan Isgor

Oregon State University College of Engineering

Distress has recently been observed in the joints of some concrete pavements, primarily in the wet-freeze states. This distress often begins in longitudinal joints, followed by transverse joints and results in the significant loss of material from the joint area. Although it may only affect approximately 10% of the concrete pavements system-wide, it greatly reduces the service life and increases maintenance costs of the pavements it effects. Primary issues that emerged from studies on this phenomenon include the importance of the timing of joint sawing, the width of the joint opening, degree of concrete or joint sealing, drainage and degree of saturation of the concrete at the joint, quality of the air void system, role of deicing chemicals, quality of curing, and the degree of restraint at the joint. This work will discuss the role of slag and its role in the reduction or mitigation of joint damage.

The Influence of Slag on Reducing Concrete Pavement Joint Deterioration

Jason Weiss and Burkan Isgor
Oregon State University

October 26th, 2020; 7:00-8:00 AM

Happy Halloween

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Pavement Joints

- The majority of concrete pavement performs well; however some joints are failing/ need repair
- A problem for an otherwise healthy pavement
- The cost is approximately $1 million dollar per mile


Taylor 2013


Weiss 2005


Taylor 2013


Weiss 2008


Weiss 2005

A Road Map for PRS and PEM Tools & Concerns

Oregon State University
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TARGET: Improve Long-Term Durability

- Freeze-Thaw
- Salt Damage
- Transport/ Chloride Ingress
- ASR
- Shrinkage & Cracking

PRS has focused on the models for performance

Recently we developed many tests that can be standardized (after a year AASTHO SOM has these to move on with through a committee/webinars)

We also have quality control/quality acceptance approaches

Weiss et al. 2015

A Road Map for PRS and PEM Tools & Concerns

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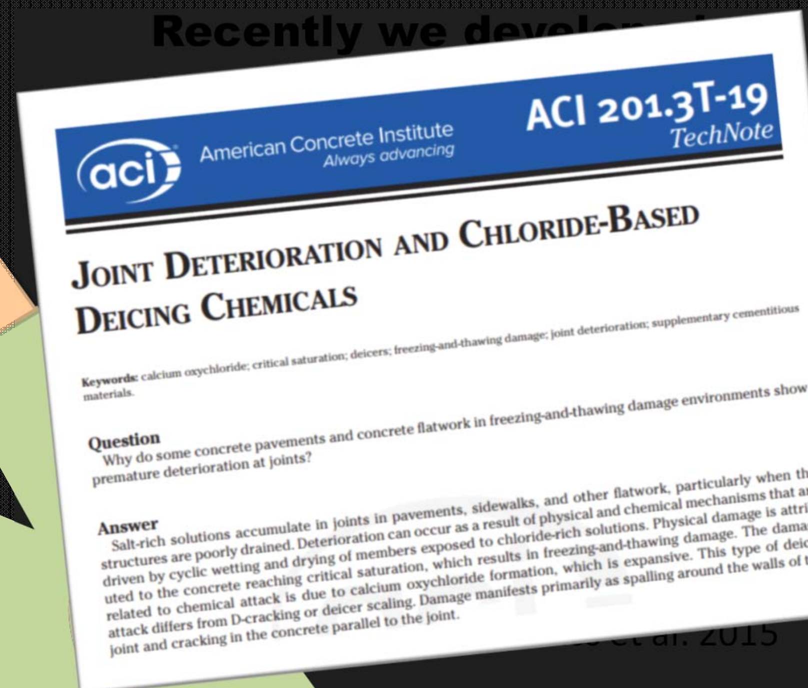

ACI 201.3T-19 *TechNote*

American Concrete Institute *Always advancing*

Joint Deterioration and Chloride-Based Deicing Chemicals

Keywords: calcium oxychloride; critical saturation; deicers; freezing-and-thawing damage; joint deterioration; supplementary cementitious materials.

Question

Why do some concrete pavements and concrete flatwork in freezing-and-thawing damage environments show premature deterioration at joints?

Answer

Salt-rich solutions accumulate in joints in pavements, sidewalks, and other flatwork, particularly when the structures are poorly drained. Deterioration can occur as a result of physical and chemical mechanisms that are driven by cyclic wetting and drying of members exposed to chloride-rich solutions. Physical damage is attributed to the concrete reaching critical saturation, which results in freezing-and-thawing damage. The damage related to chemical attack is due to calcium oxychloride formation, which is expansive. This type of deicer attack differs from D-cracking or deicer scaling. Damage manifests primarily as spalling around the walls of the joint and cracking in the concrete parallel to the joint.

... et al. 2015

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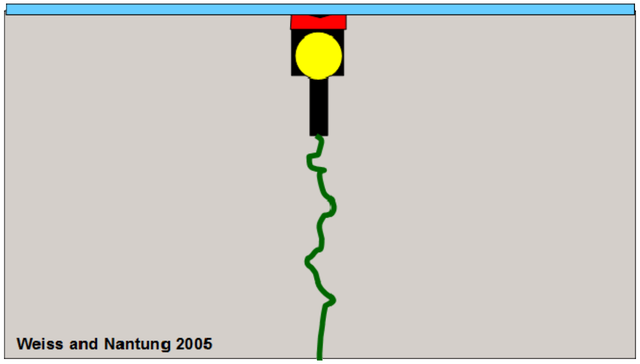
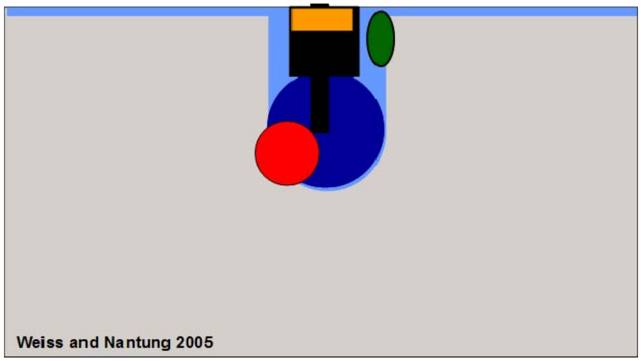
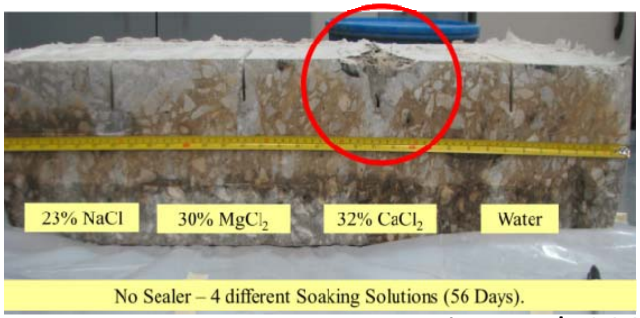
Weiss 2005

Toward a Working Mechanism

- Examined saw cutting and curing at joints
- Fluid enters joint is trapped
- Saw cut joints not opening to drain (higher early strength, thicker, increased tie bars)
- As a result, fluid can not drain out easily to drainable subbase under the PCCP
- Silicone sealant & backer rod limit drying of trapped fluid which can increase saturation and potentially lead to crystal growth, chemical reaction or pressure







Weiss et al. 2005

Potential Blame

- Contractor/Construction – Overvibration, poor mixture designs, insufficient air
- Pavement Design – too much steel, poor drainage, too thick a pavement
- Deicer supplier – ‘super salts’ ‘eat’ pavements
- Admixture supplier – Bad air systems, ‘new air’
- Hand placement vs machine placement
- Sulfates and ettringite
- Anti-icing deicing practice
- D Cracking, aggregates etc..
- Saw cutting crews/techniques
- Saw cutting vs forming

Salt Damage

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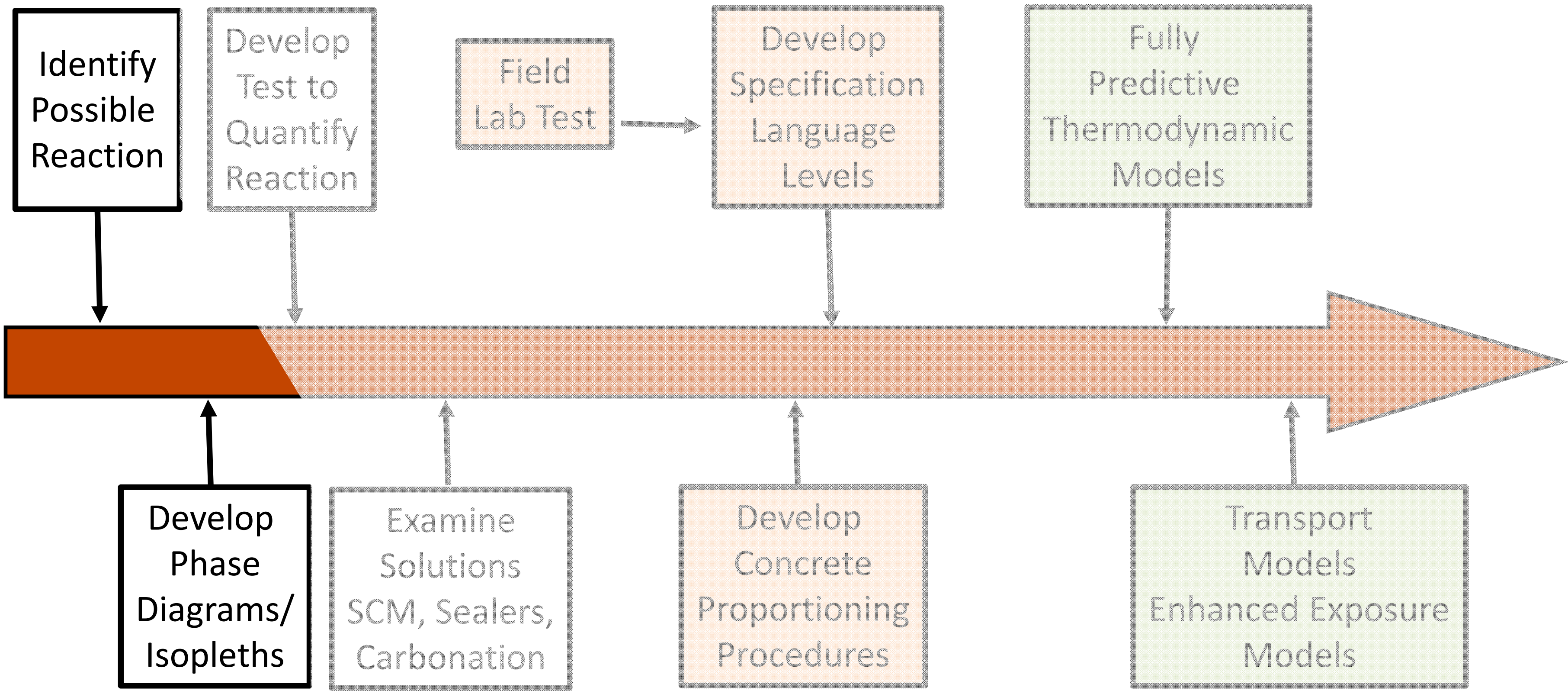
- For approximately 15 years concrete pavements have been observed to show damage at the joints

- Much speculation has been made to the cause of this damage however it seems to now be due in large part of fluid induced freeze-thaw damage and $CaCl_2$, $MgCl_2$ damage

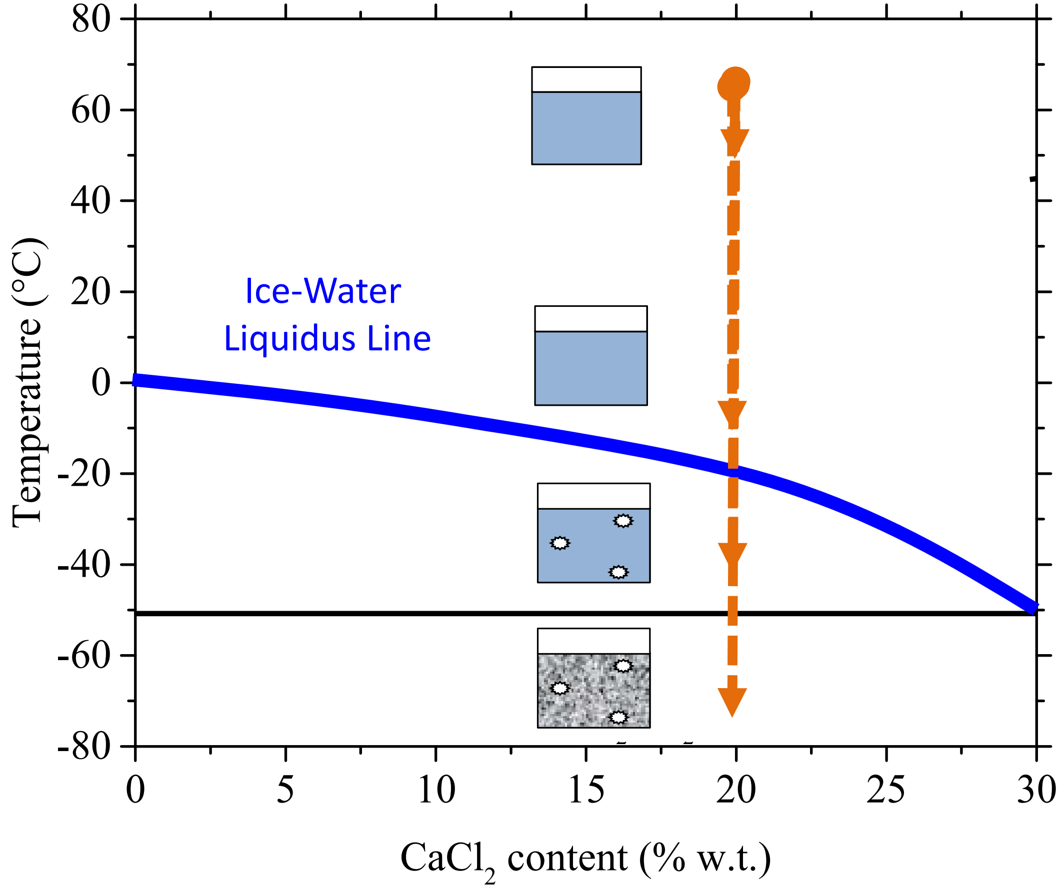
- We have come a long way but have some solutions

Overall Timeline



Phase Diagram For $CaCl_2$-H_2O Solution

- NaCl salt most common deicers used in practice
- Many times it is blended with $CaCl_2$ or $MgCl_2$
- We will discuss blends later however for now lets focus on $CaCl_2$
- Ice forms as we cross the liquidus line
- All solution solidifies below the eutectic temperature



What Causes the Calcium Oxychloride to Form

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- NaCl salt most common deicer used in practice; many times it is blended with $CaCl_2$ or $MgCl_2$
- For each system the results are a little different but lets focus on $CaCl_2$ as the salt: Reactions occur with C_3A, Afm, Aft, $Ca(OH)_2$
- Kuzel Salt and Friedel Salt – They occur; likely not issue
- Calcium oxychloride forms due to reaction with $Ca(OH)_2$

$$3Ca(OH)_2 + CaCl_2 + 12H_2O \rightarrow CaCl_2 \cdot 3Ca(OH)_2 \cdot 12H_2O$$

Calcium Oxychloride

Phase Isopleth For $CaCl_2$-H_2O-$Ca(OH)_2$

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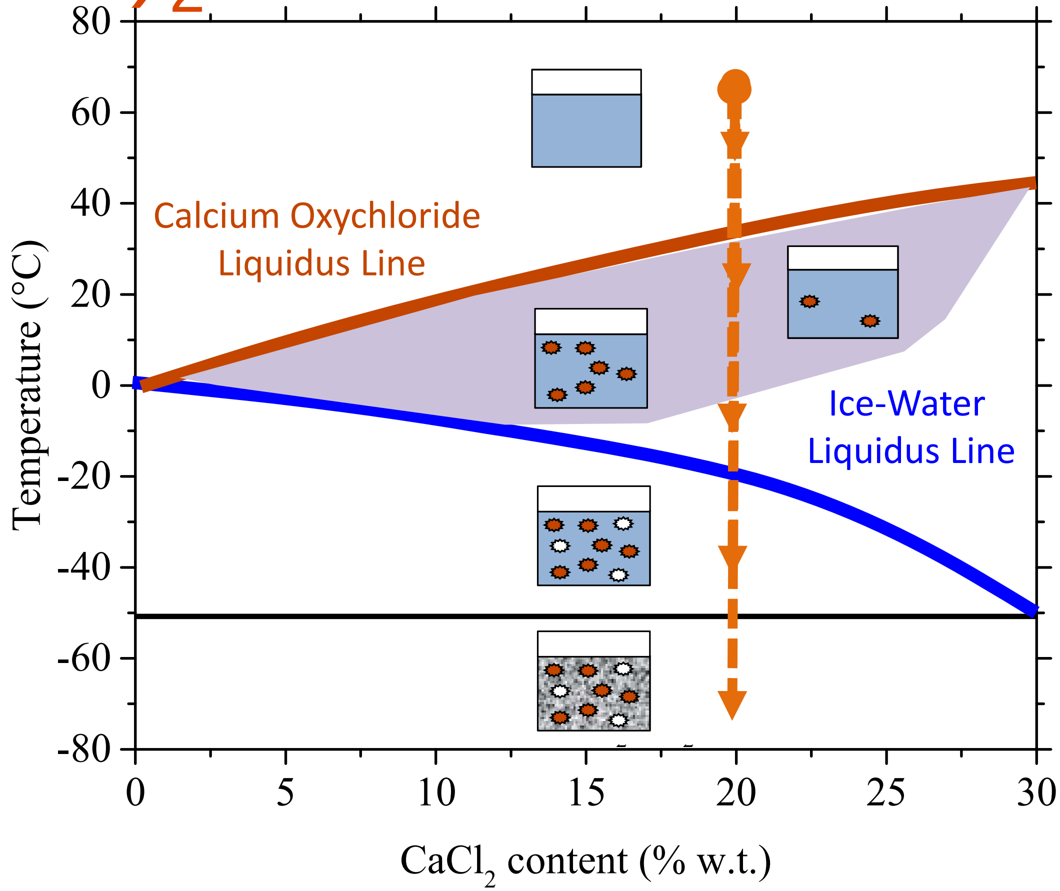
- However in cement paste there are other species in the pore solution
- Here we see that when the solution contains calcium hydroxide an additional phase forms
- This phase has some implications on the performance of the system



Qiao et al. 2017

The Role of SCM

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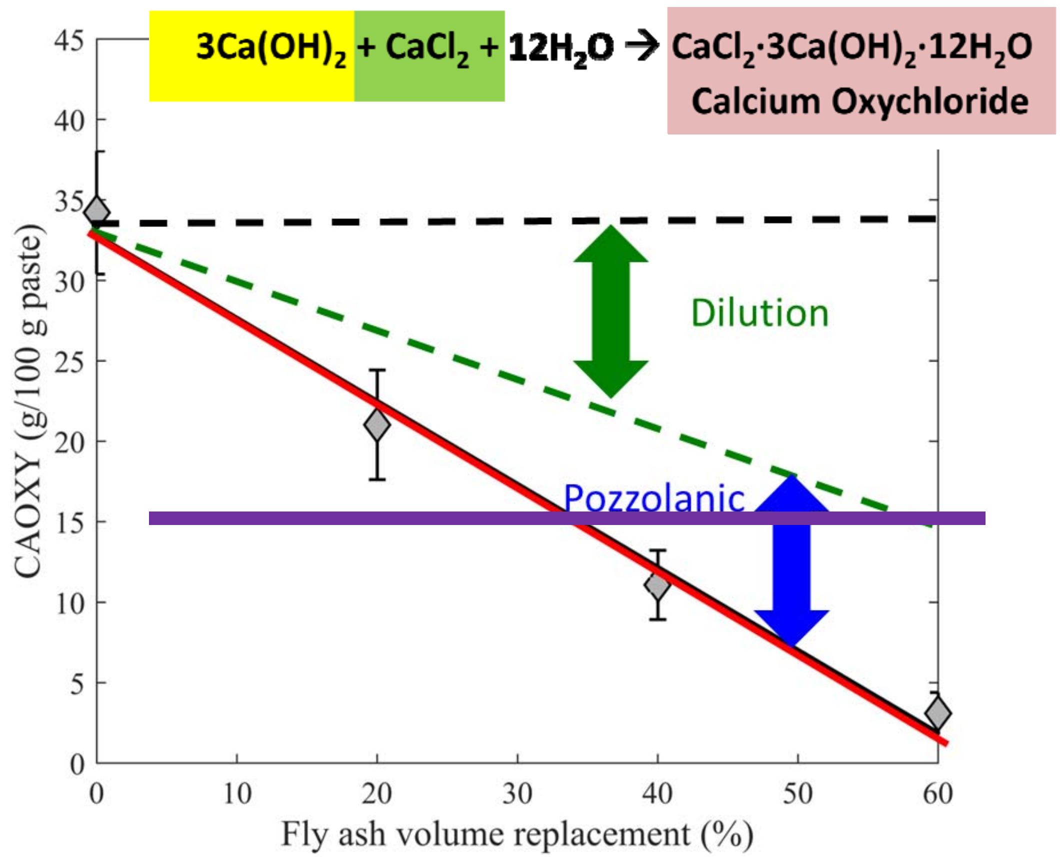
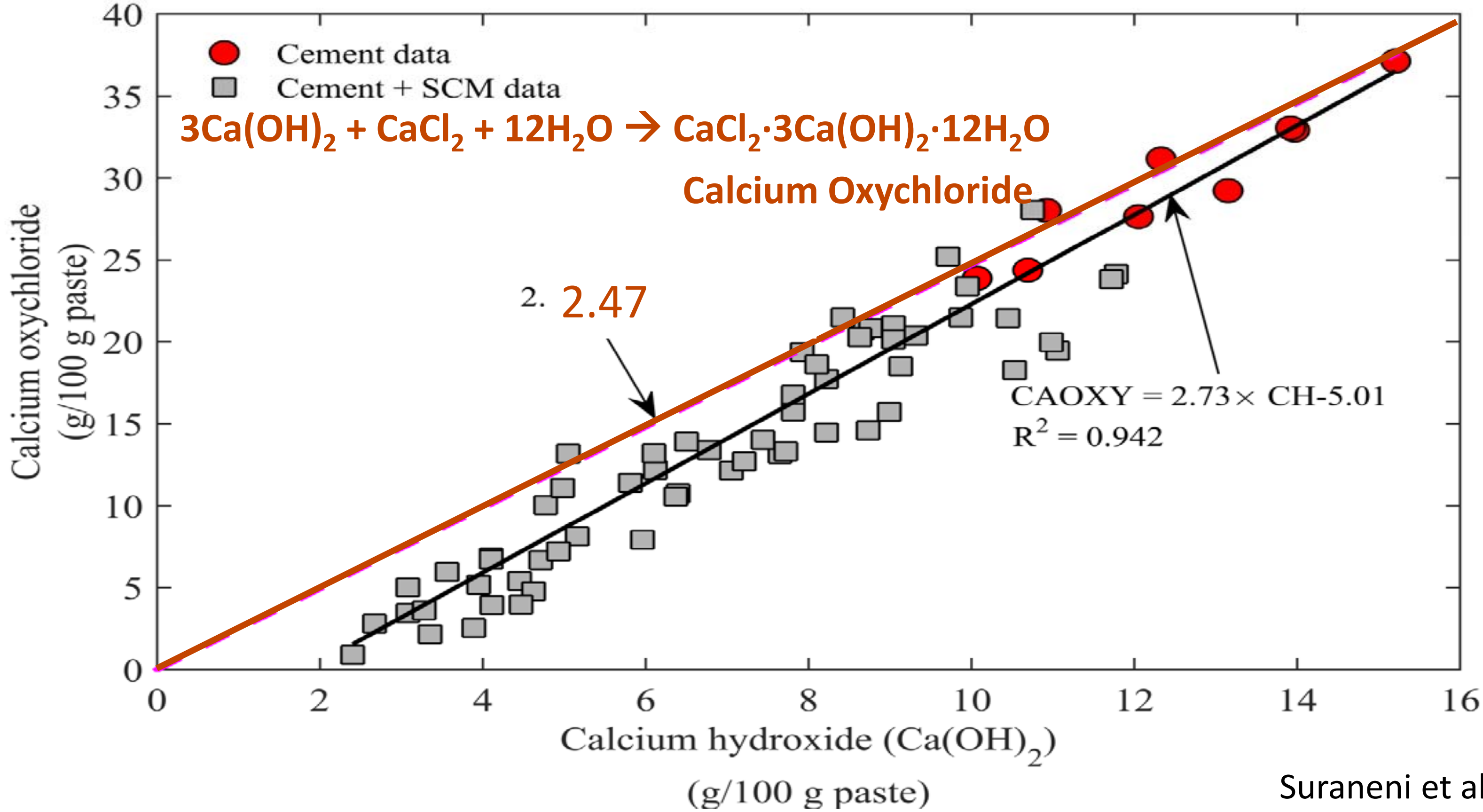
- Effect of Dilution (Less CH)
- Pozzolanic Reaction (Less CH)
- Limiting Factor
- Mixture Design



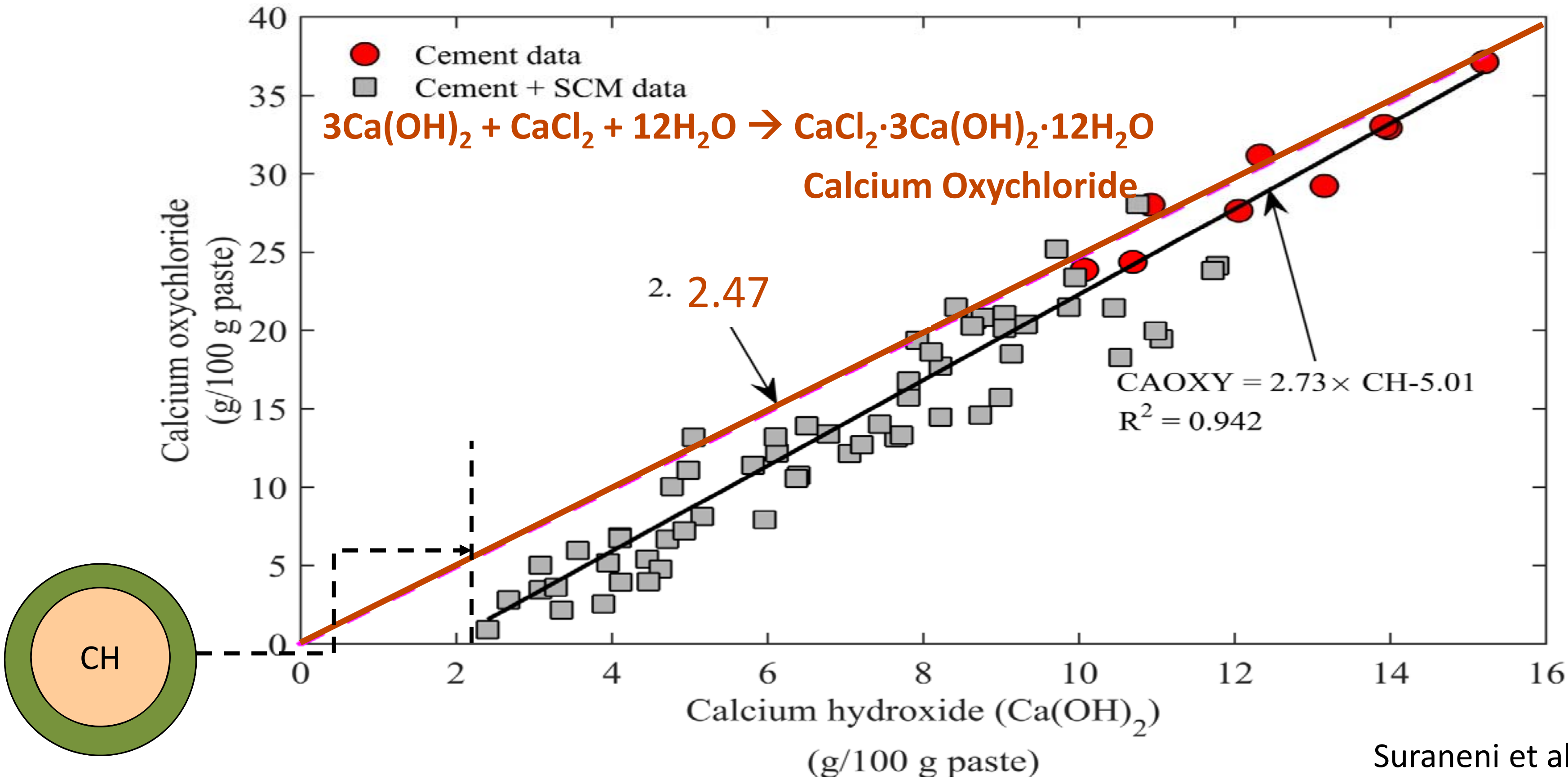
Monical et al. 2016

Relating CH and CAOXY



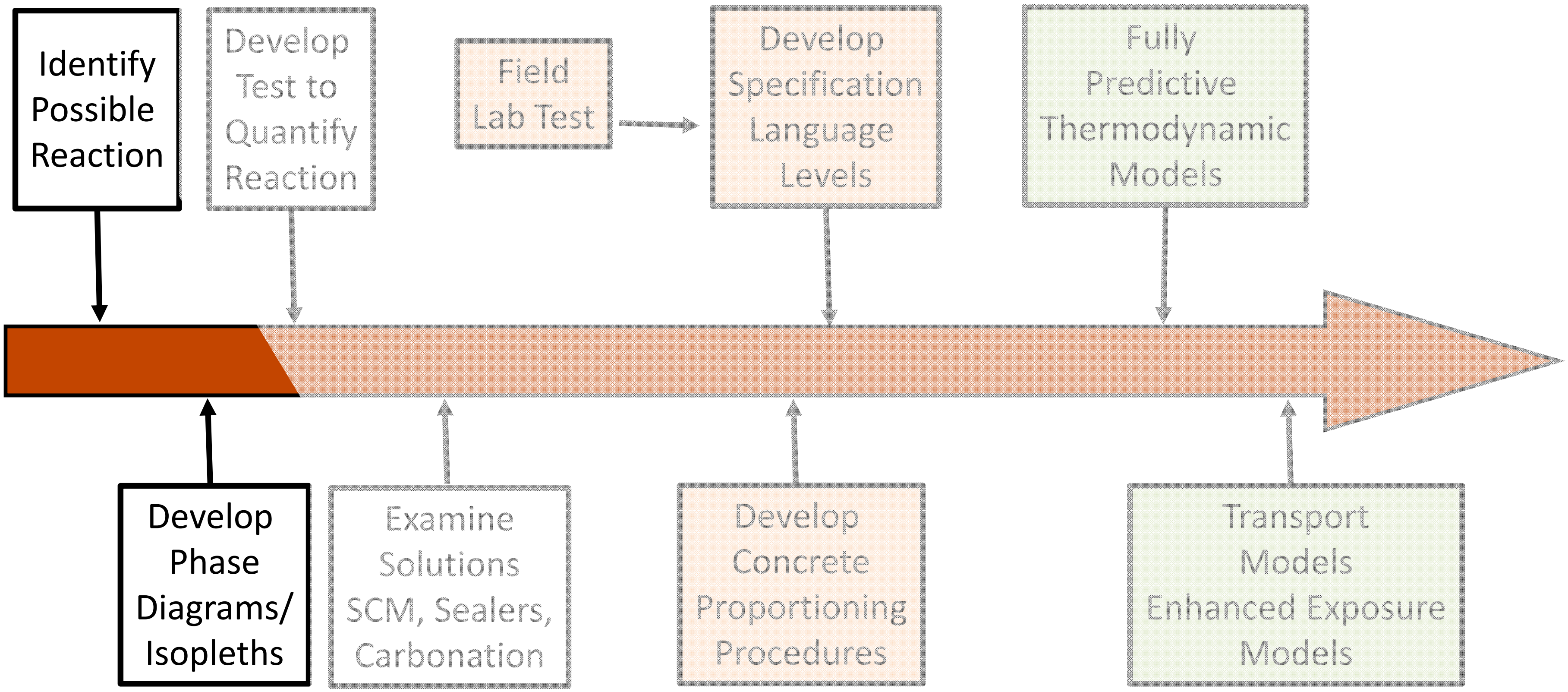
Suraneni et al. 2016d

Relating CH and CAOXY



Suraneni et al. 2016d

Overall Timeline



Test - AASHTO T365

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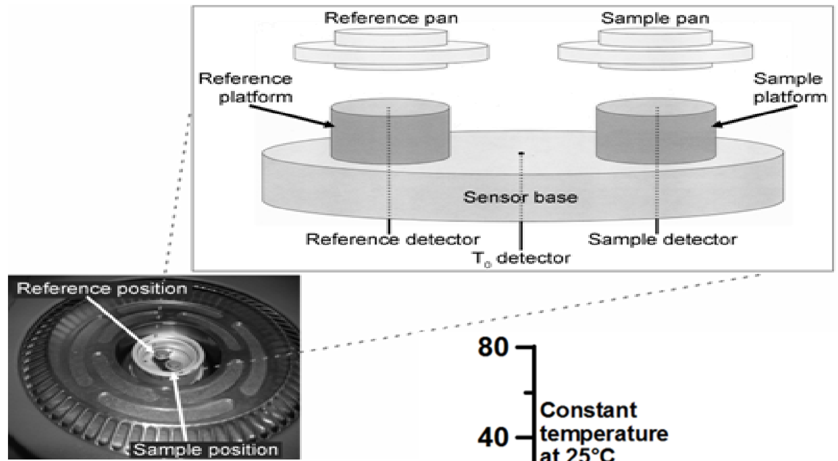
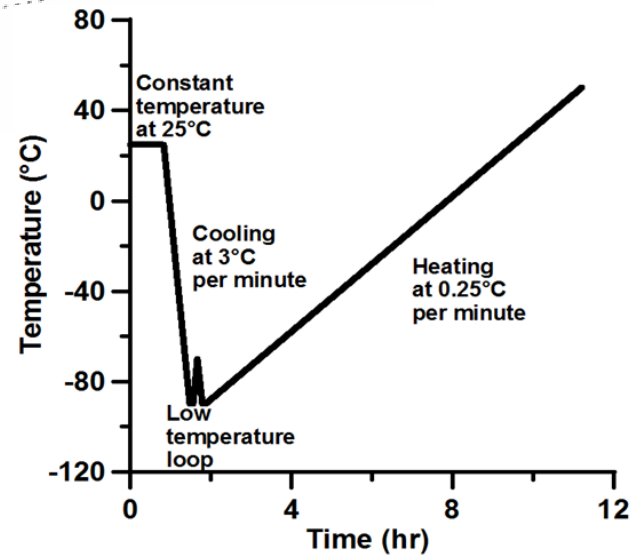
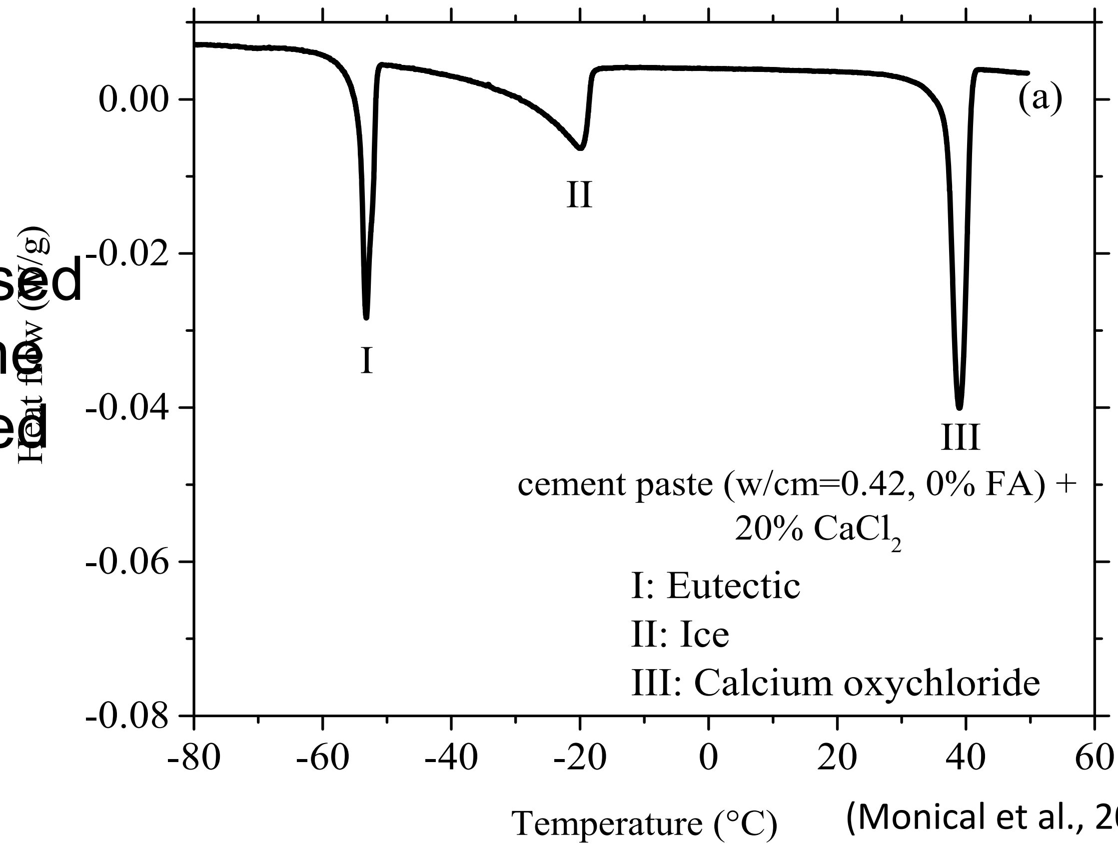
- Cement paste is ground and placed in a salt solution.
- Pan is moved into the cell.
- Thermal Cycle to cause CaOxy to form and we can quantify using heat





A Test to Quantify Damage (LTDSC)

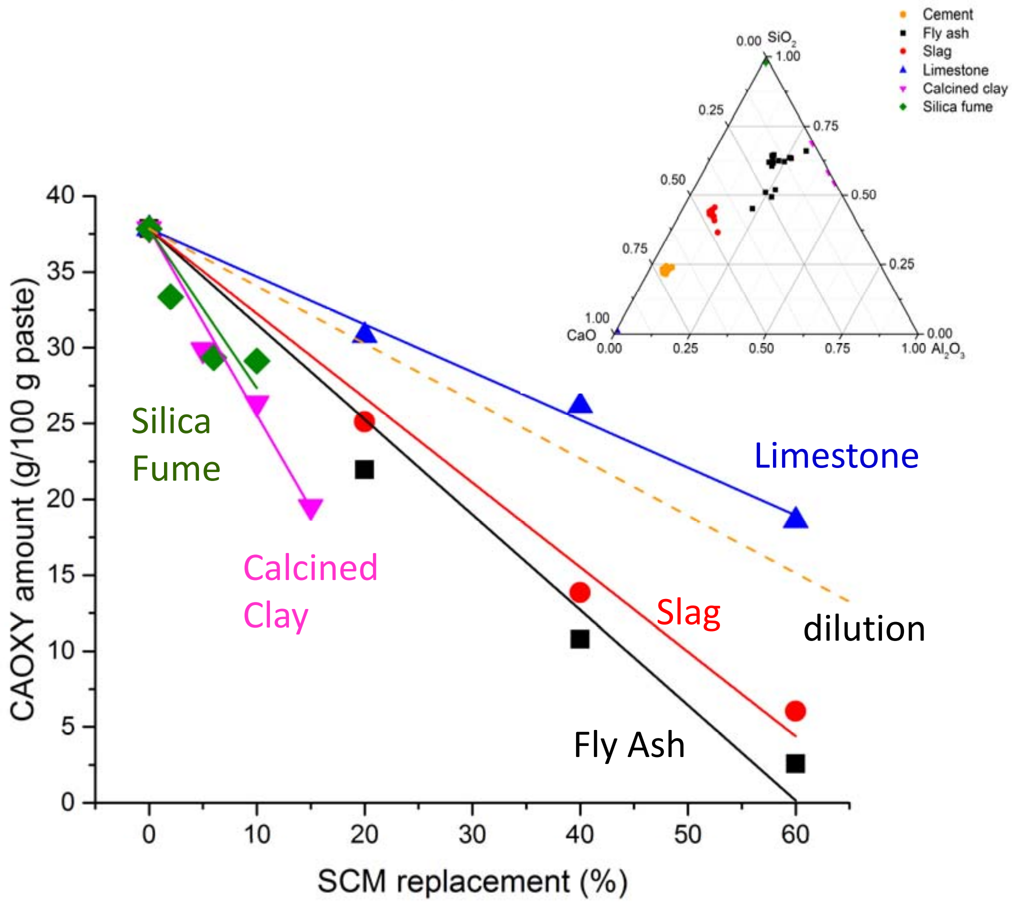
- Low Temperature – Differential Scanning Calorimeter (LT-DSC)
- Temperature is decreased from 50 °C to -80 °C, the sample is then re-heated
- Uses powder with $CaCl_2$
- Notice heat flow peaks at various phase formations



(Monical et al., 2015)

CH Reduces with Slag

- Its interesting to note that the use of slag reduces CH
- As a result the CaOxy is expected to be reduced
- This is interesting as slag is not a pozzolan



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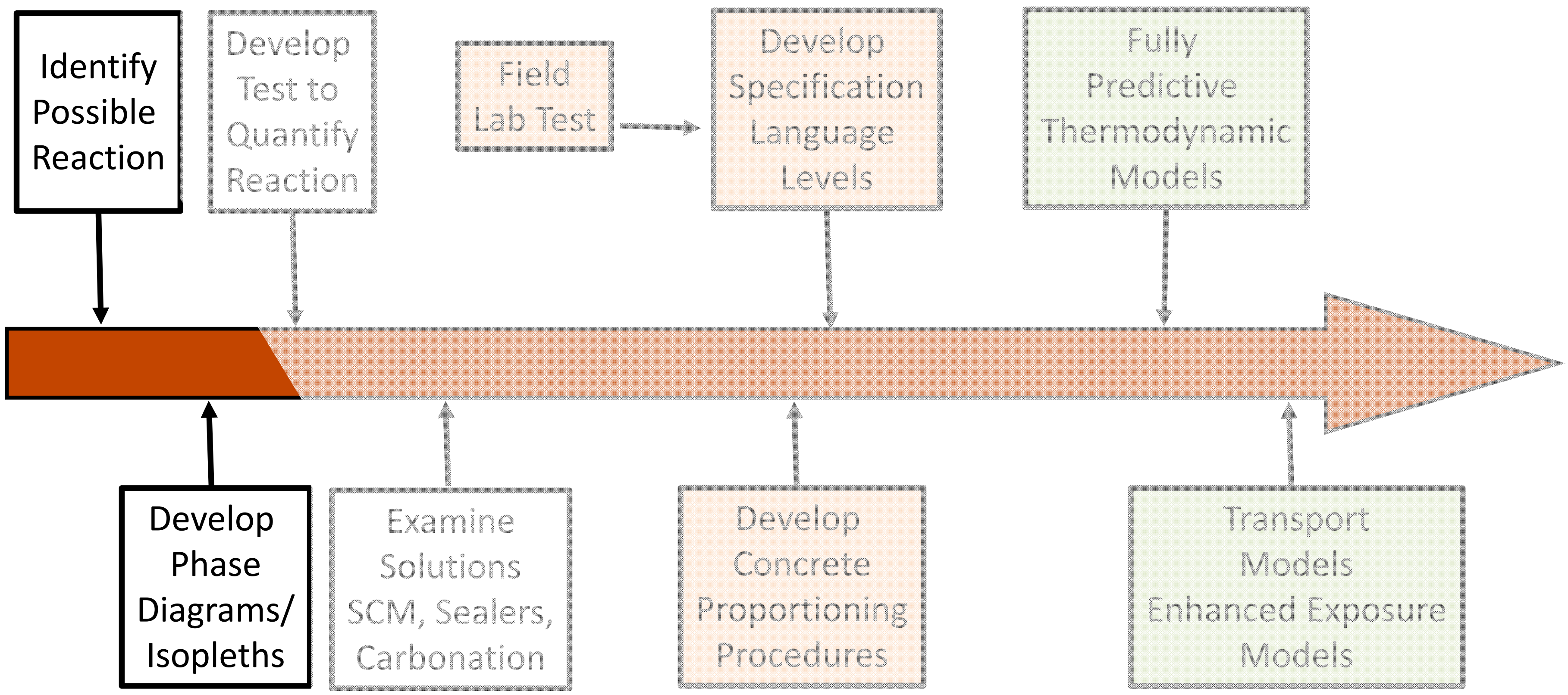

Thermodynamic Model

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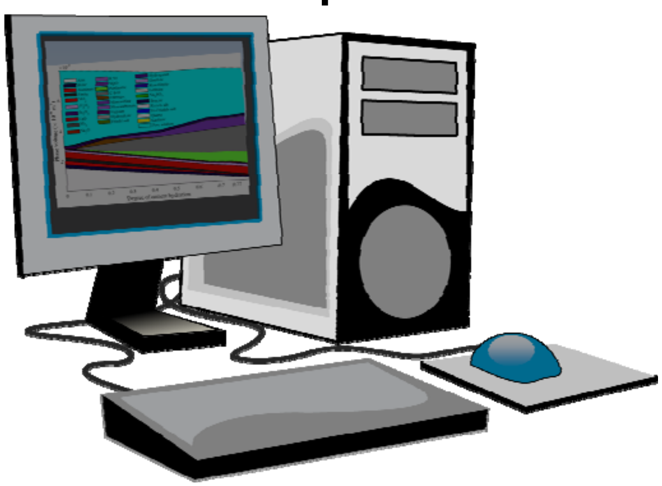
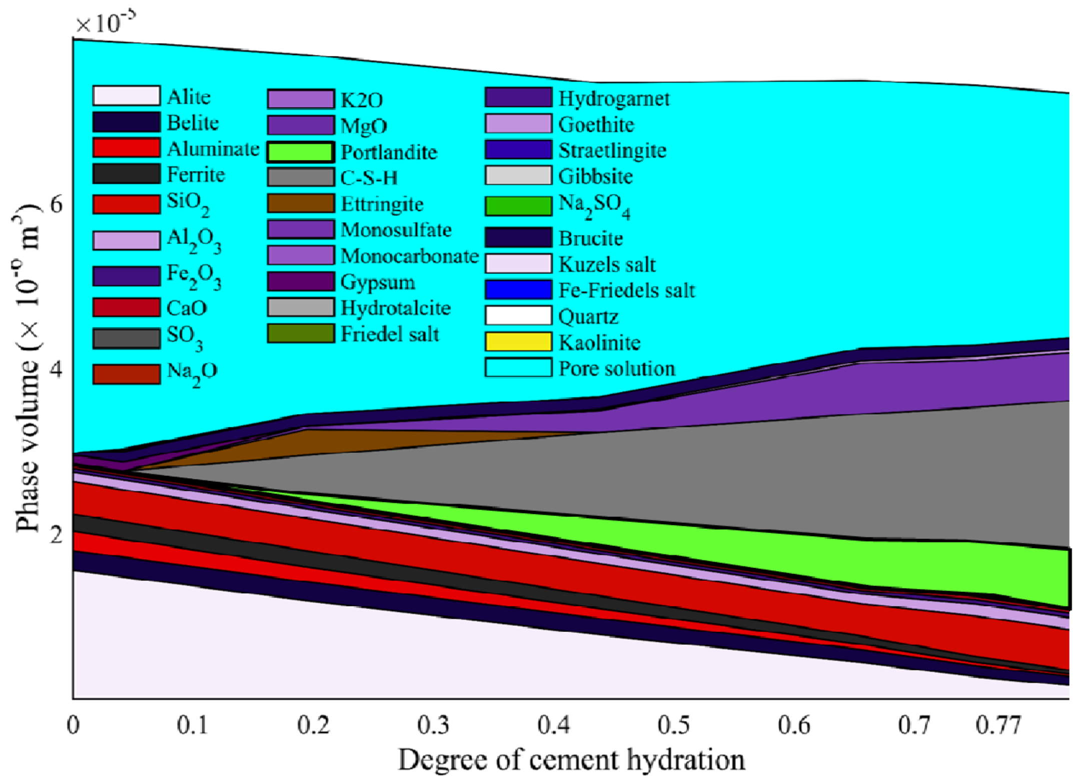
- Using GEMS to predict the reacted products
- Specifically examining the CH production

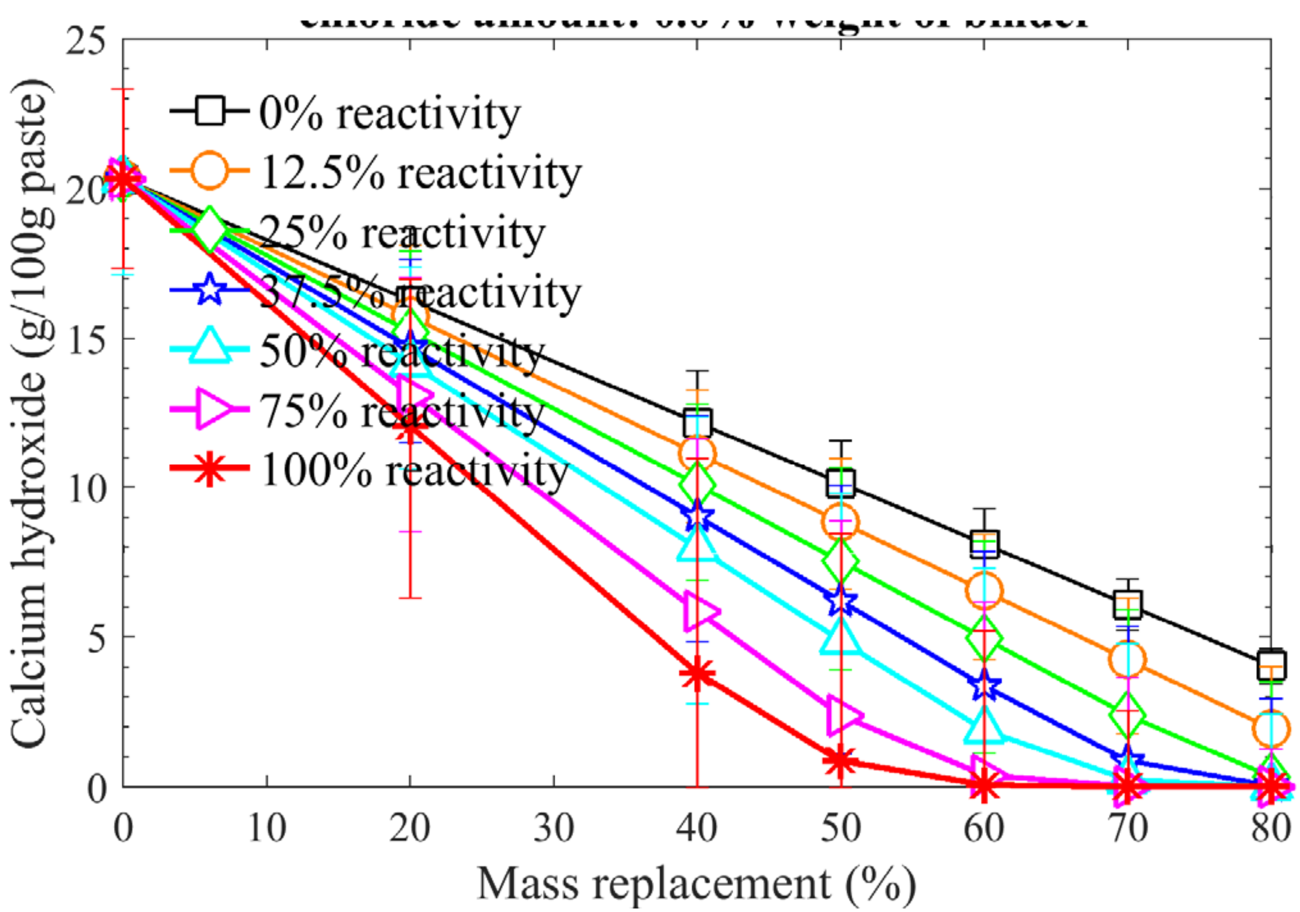




Azad et al. 2016

CH Reduces with Slag

- As slag is added the CH value decreases
- Here we see simulations that assume different extents of rxn



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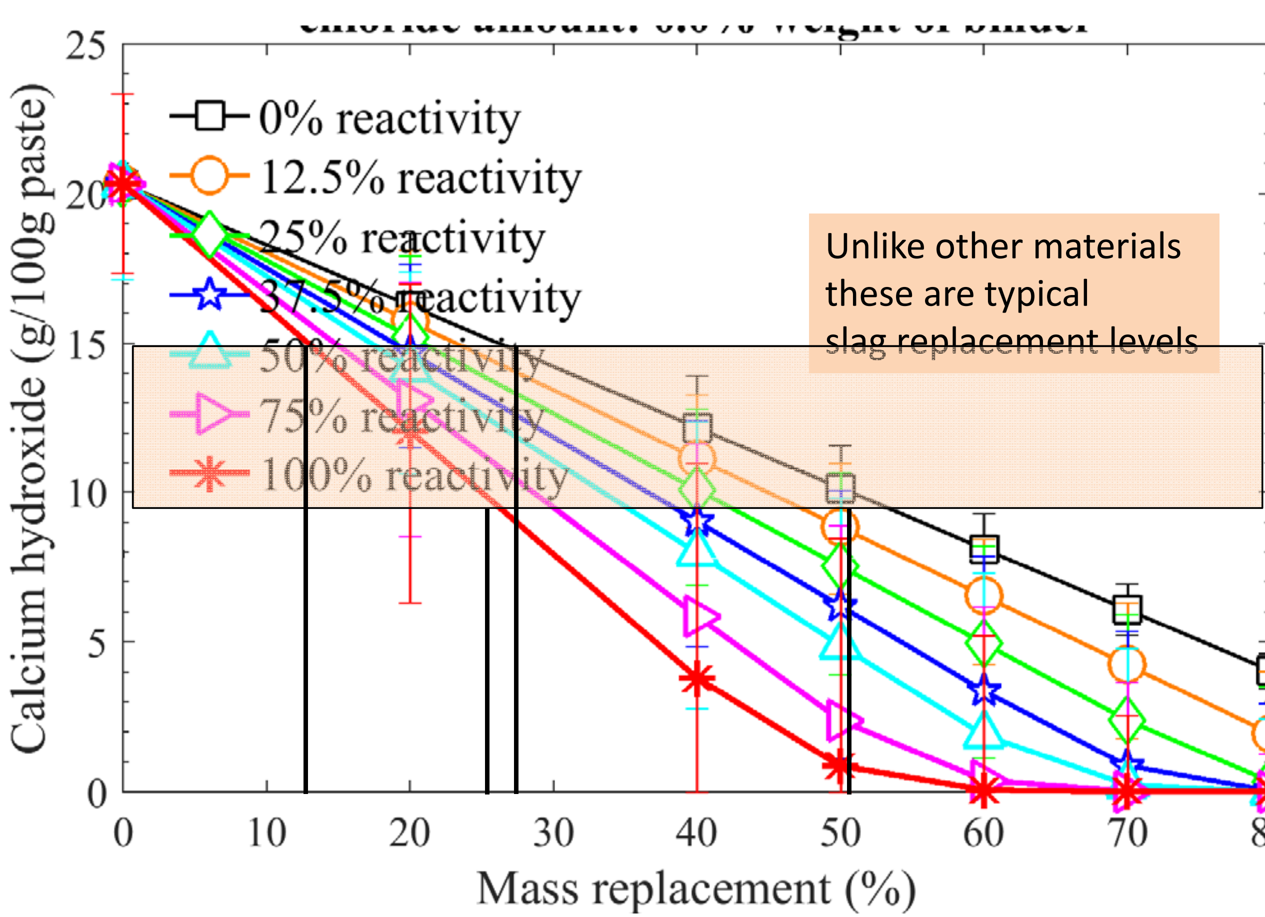

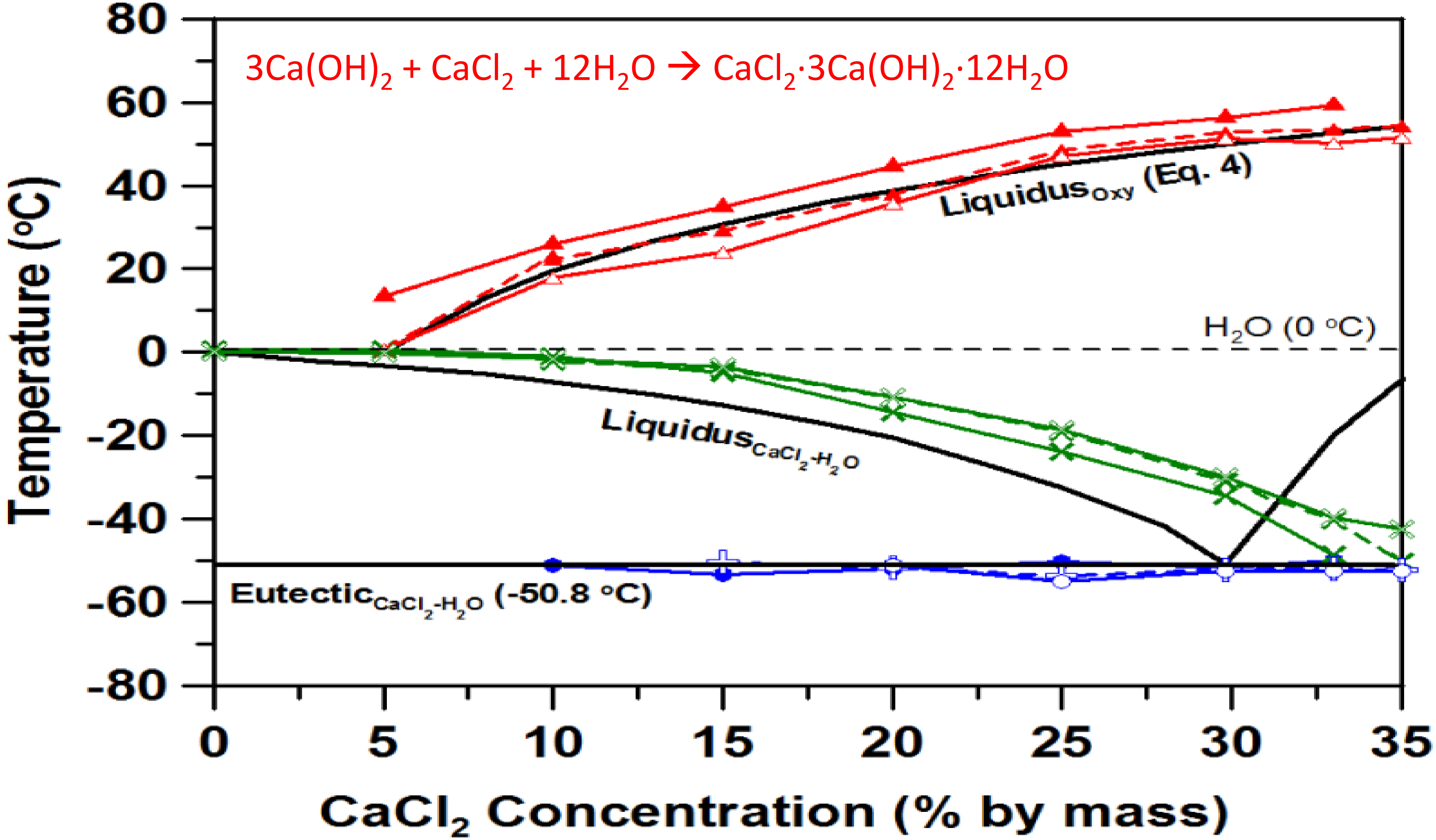

Farnam et al. 2013

Volume Change

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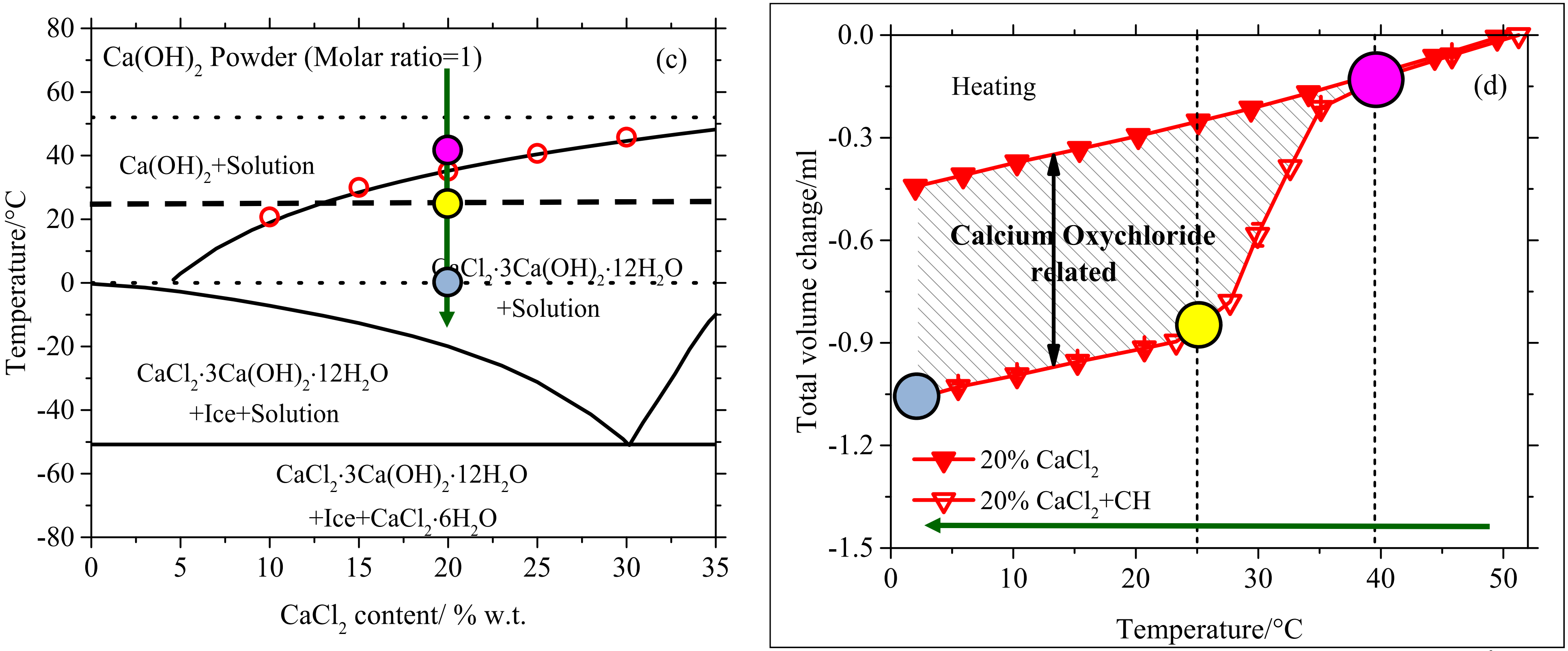

Qiao et al. 2017

Calcium Oxychloride

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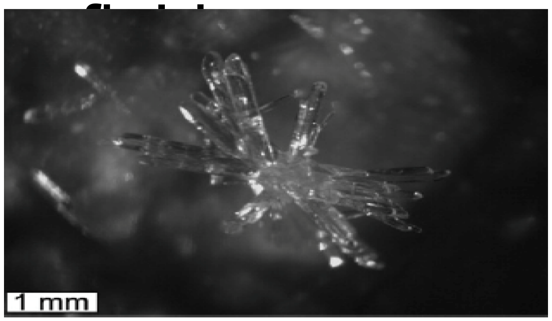
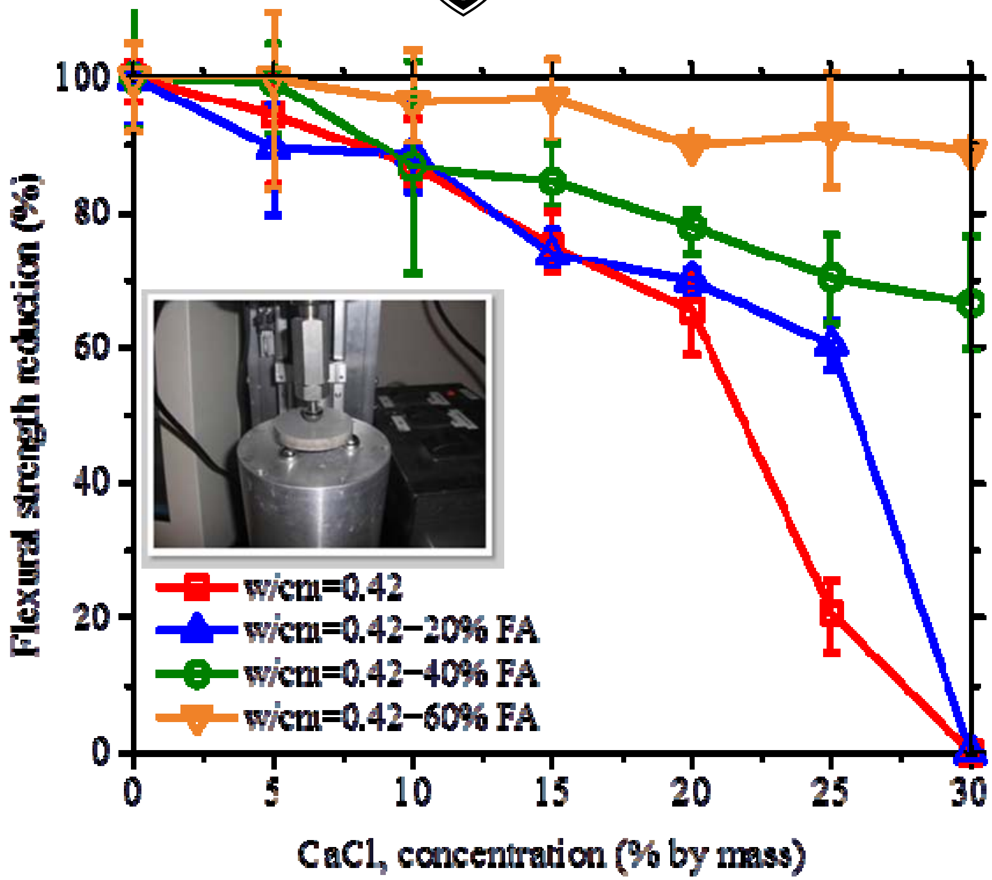
- Ca-oxychloride transforms from liquid to solid
- Damage manifests as paste flaking that is observed in the



Peterson et al. 2013

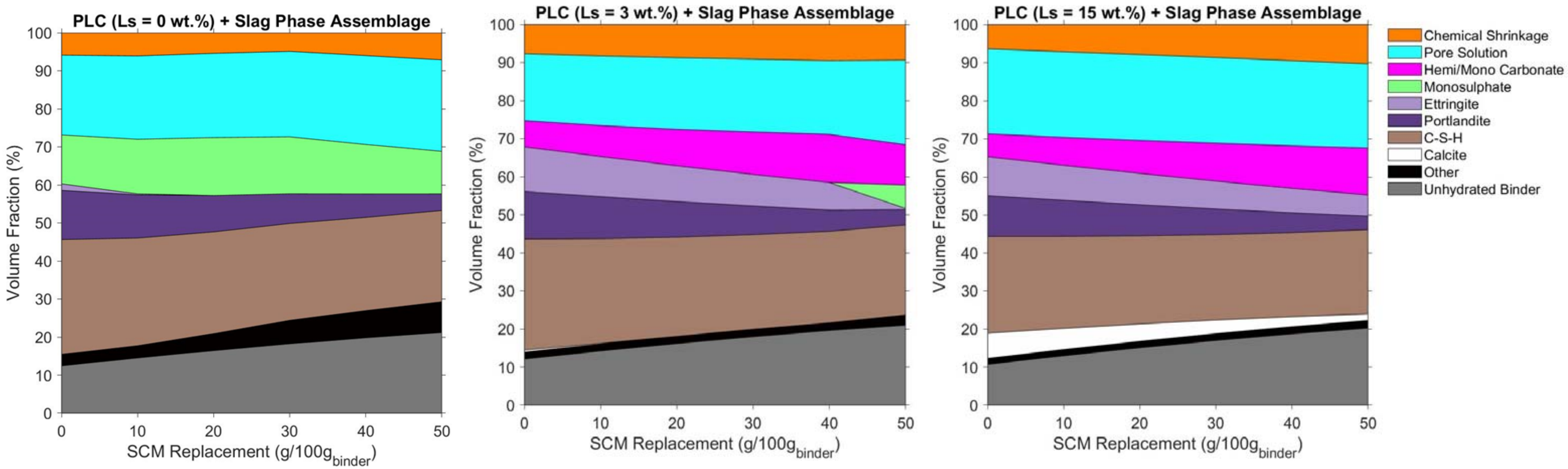
Qiao et al. in 2017



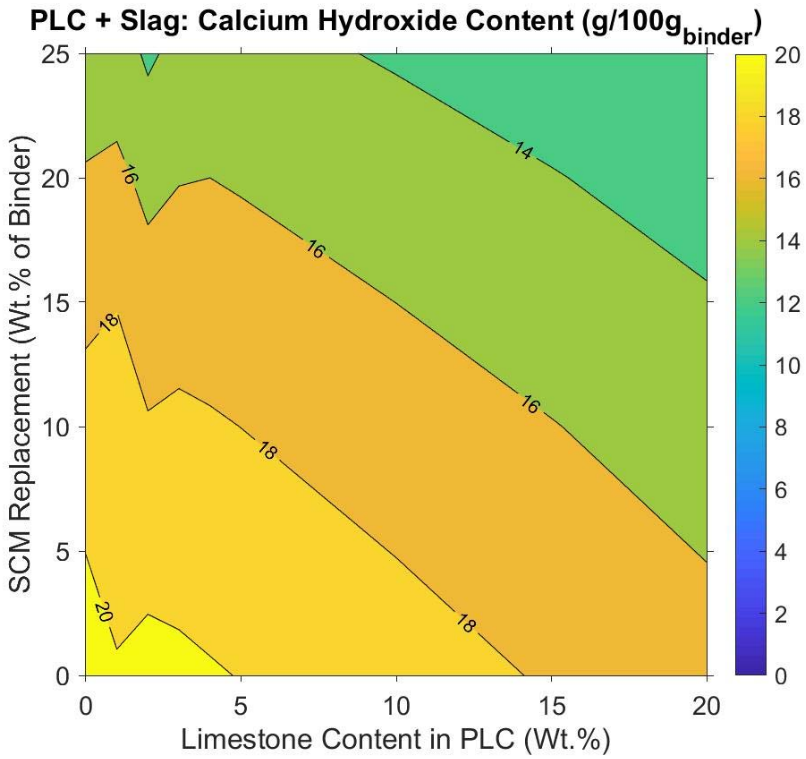
Qiao et al. in 2017

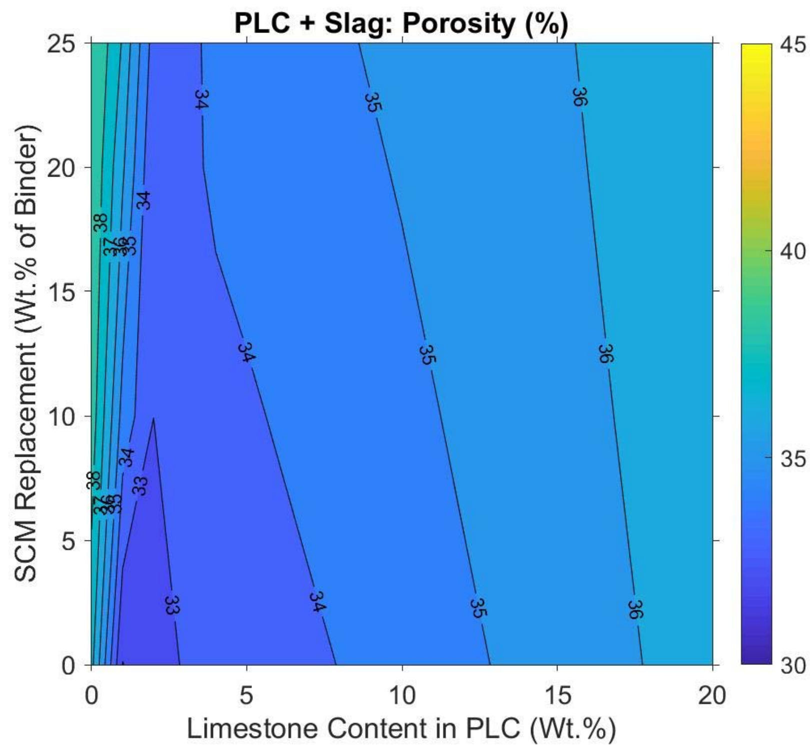
Thermodynamic Model

- As limestone is increased, the chemical shrinkage increases and the monosulfate converts to ettrinigte and hemi/mono carbonate



PLC + Slag


PLC + Slag: Calcium Hydroxide Content (g/100g$_{binder}$)
SCM Replacement (Wt.% of Binder)
Limestone Content in PLC (Wt.%)
0
5
10
15
20
25
20
18
16
14
12
10
8
6
4
2
0


PLC + Slag: Porosity (%)
SCM Replacement (Wt.% of Binder)
Limestone Content in PLC (Wt.%)
0
5
10
15
20
25
30
35
40
45
33
34
35
36
37
38

Numerical case studies

Cement:

C_3S: 52.2%
C_2S: 21.6%
C_3A: 8.1%
C_4AF: 7.6%
SO_3: 3.0%
Na_2O_{eq}: 0.2%
MgO: 2.3%

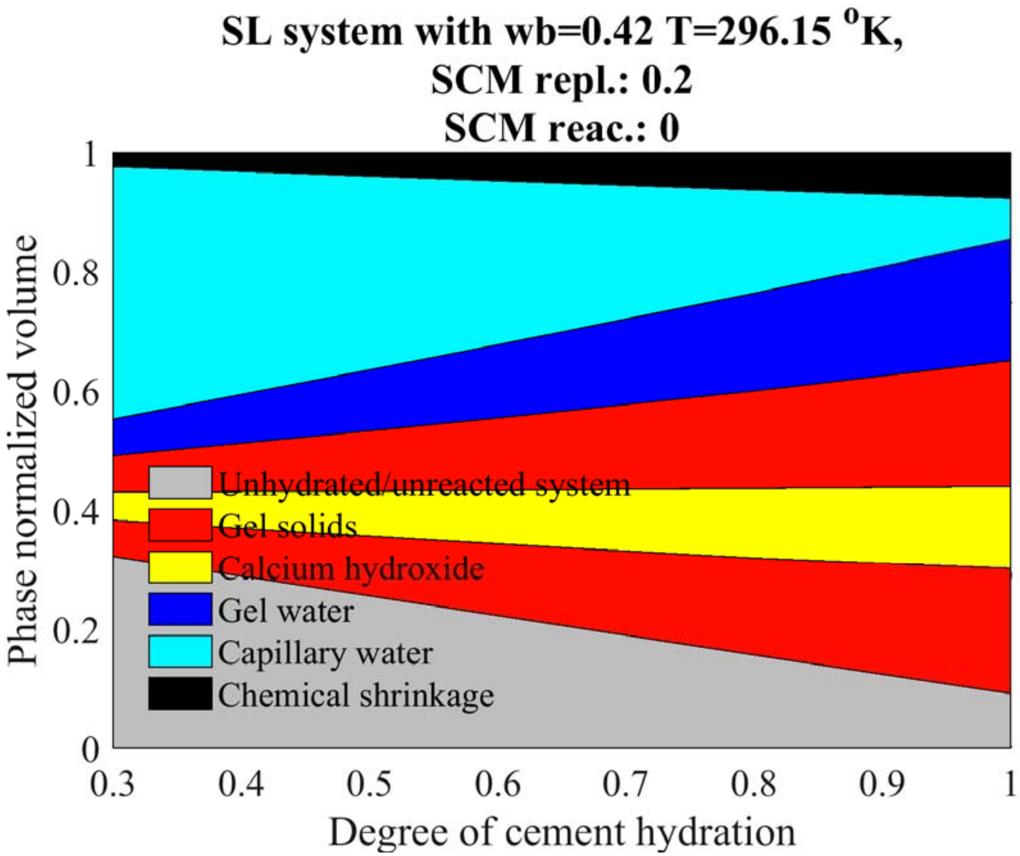
Slag:

SiO_2: 35.0%
Al_2O_3: 12.0%
Fe_2O_3: 1.0%
CaO: 40.0%
SO_3: 9.0%
Na_2O_{eq}: 0.6%

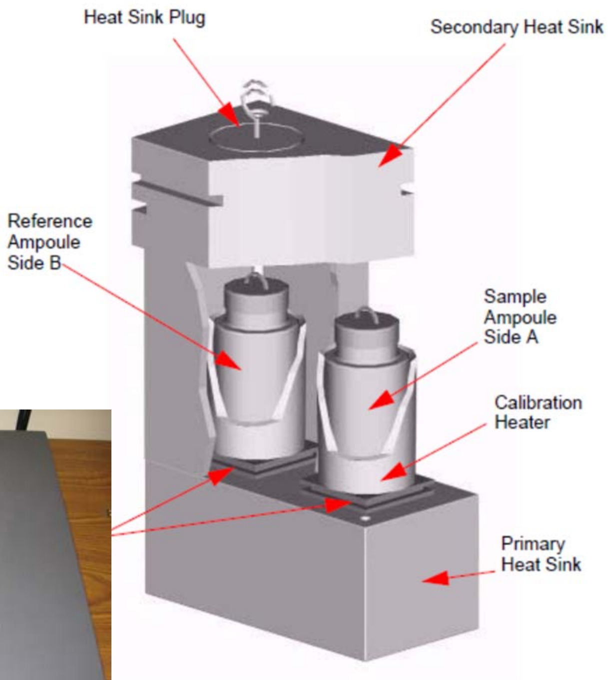
w/b = 0.42
T = 23 ^oC

- Mass replacement: 0-80%
- SCM reactivity: 0-60%

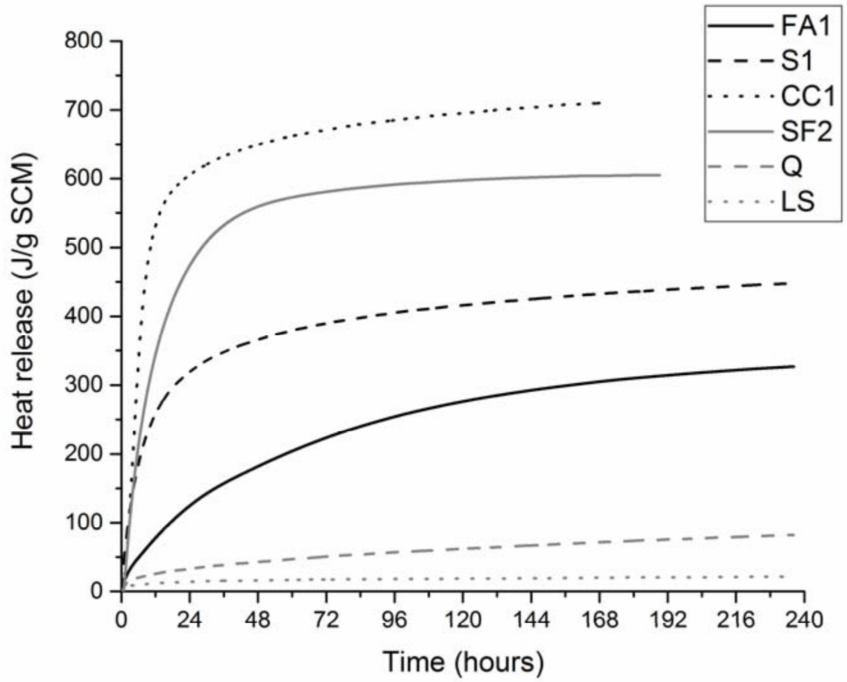
[1] Shehata, Thomas 2000
[2] PCA bulletin 15th edition, 2011



Isothermal Calorimetry



Cutaway View
Twin Configuration
One of Eight Calorimetric Channels



Suraneni et al., 2016b

New pozzolanic test (Being Incorrectly Applied to Slag)

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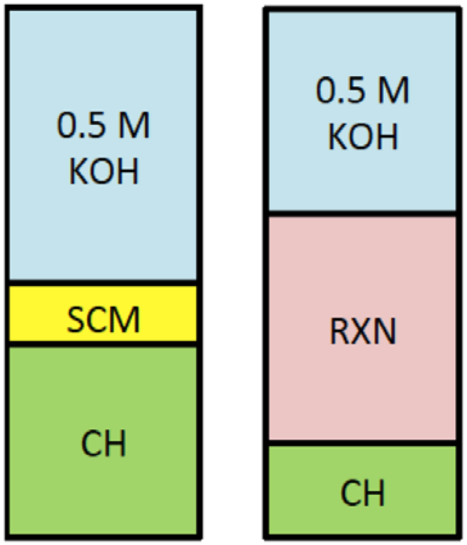
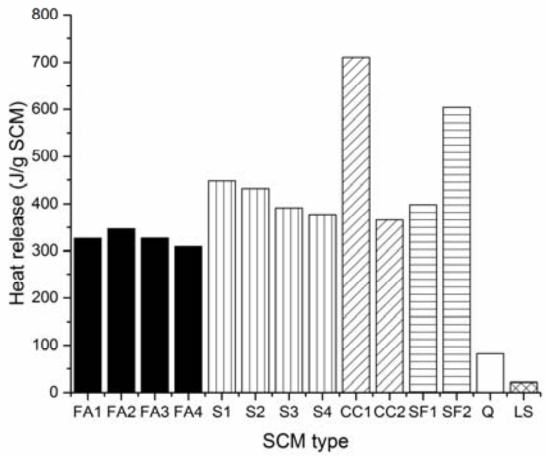
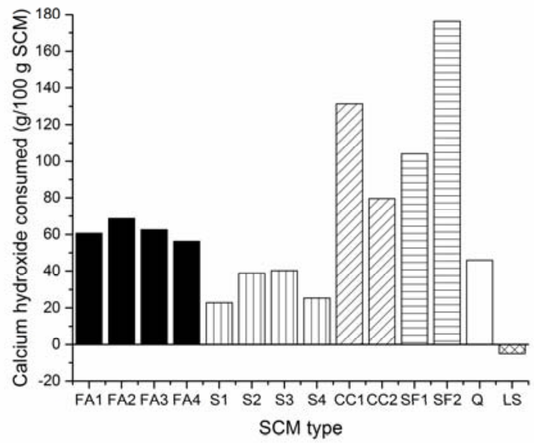
- Measurement of heat release, CH consumption, and bound water for SCM-CH systems



- CH/SCM = 3: 1 (by mass)
- 0.5 M KOH solution
- w/s = 0.9
- Temperature = 50 °C
- Measure heat release by IC and CH consumption by TGA for various SCMs
- Adapting interpretation for Slag (Ongoing work DOE)





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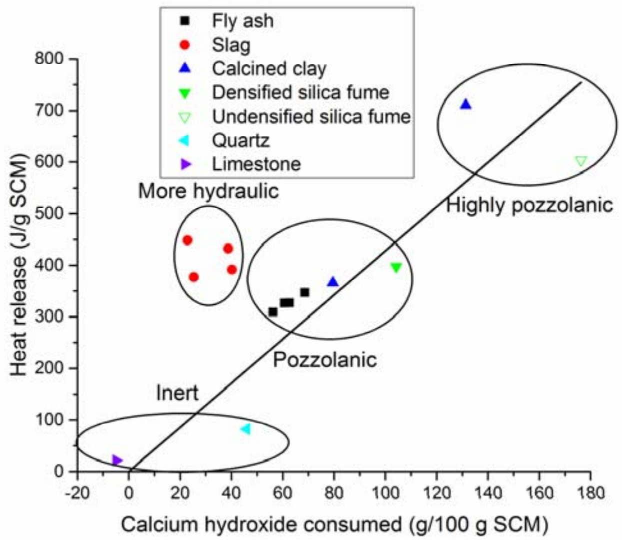
- Sixteen fly ashes
- Four slags
- Two calcined clays
- Two silica fumes
- Limestone
- Quartz
- Ground LWA
- Other non-traditional SCMs



Suraneni et al., Cement and Concrete Composites, 2016b

Sustainability in Construction a Look at Portland Limestone Cement

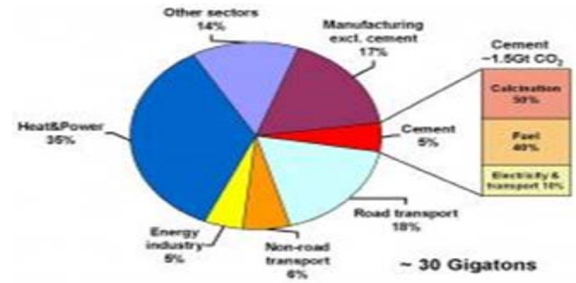
Jason Weiss, jason.weiss@oregonstate.edu, Originally developed 2011
Head School of Civil and Construction Engineering, Edwards Distinguished Professor

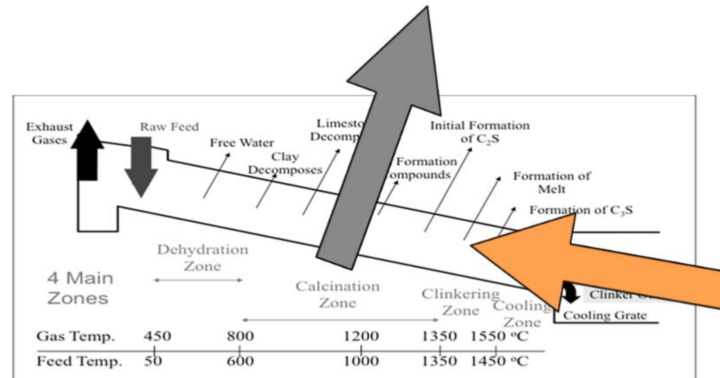
Cement and CO_2 Production

- You will hear cement accounts for 7-8% of global CO_2 (Mehta 1998)
- What/Where is the CO_2 coming from
  - Calcination
  - Combustion
  - Transportation

$$CaCO_3 \xrightarrow{\text{yields}} CaO + CO_2$$

$$C + O_2 \xrightarrow{\text{yields}} CO_2$$





- Concrete has relatively low carbon emission per unit; however widespread use of concrete makes it a major contributor to manmade CO_2 emissions

Concrete Sustainability

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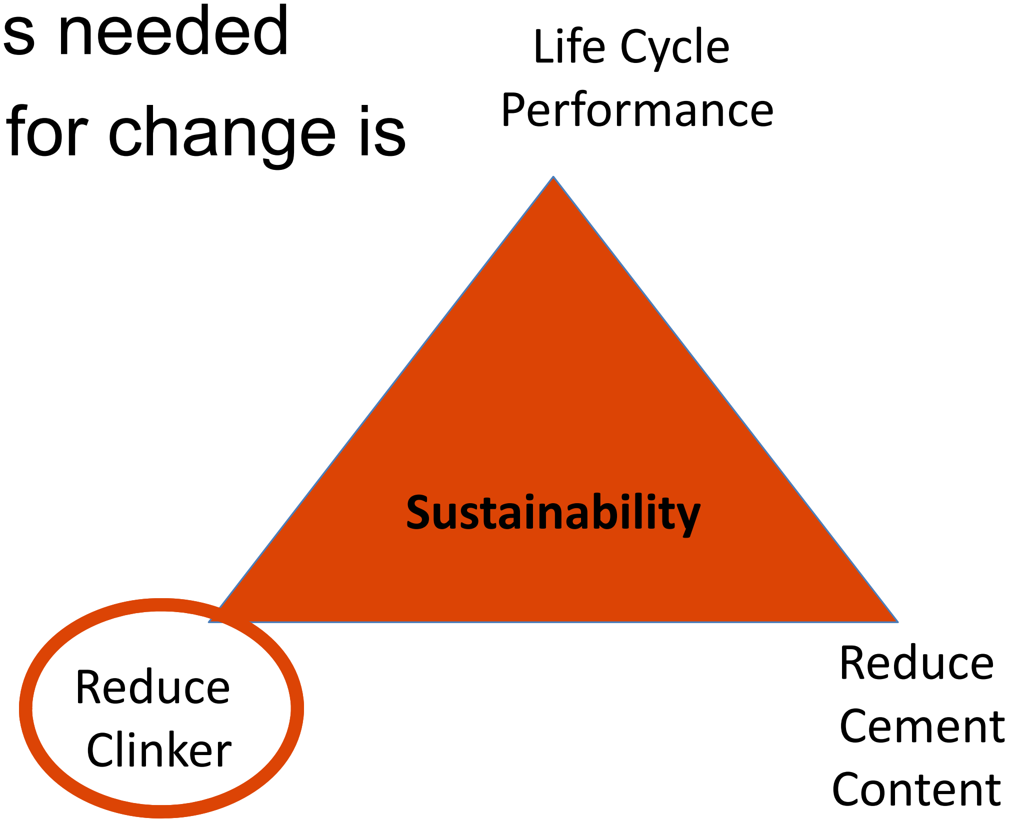
- I will suggest that change is needed
- I will suggest that the time for change is



- Three Prong approach

Approaches to Reduce Clinker Content

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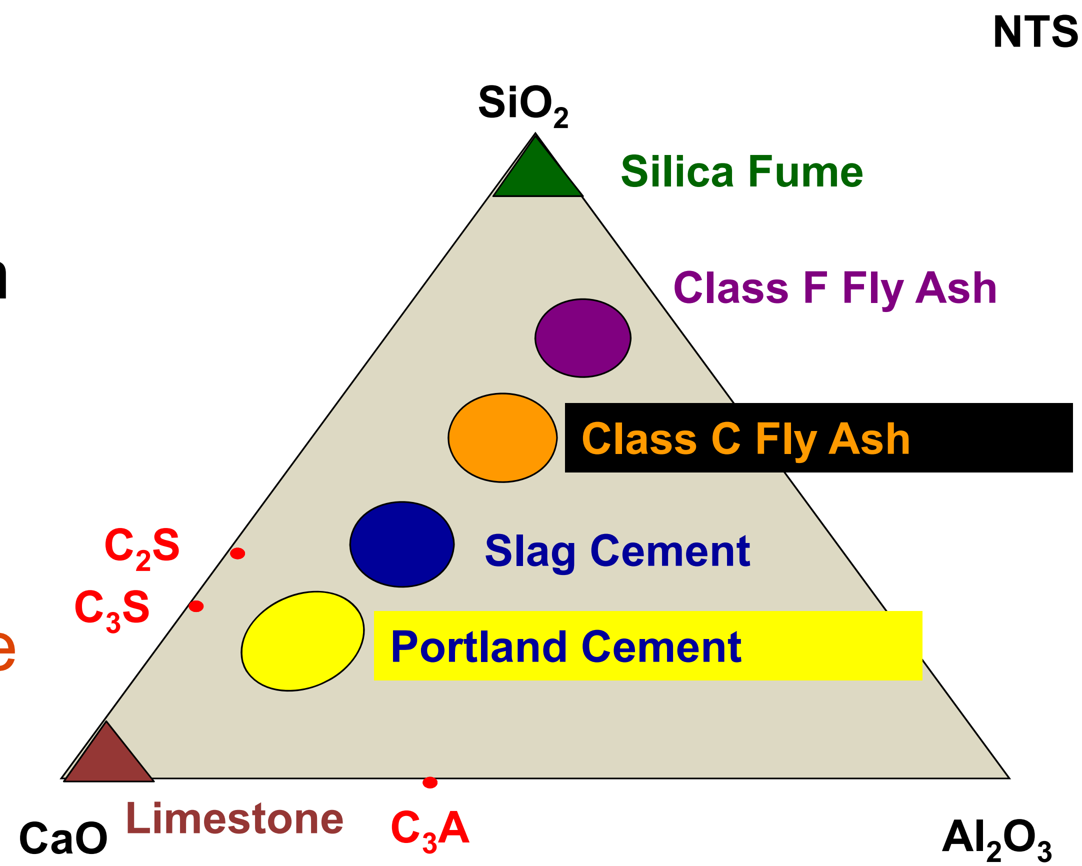
- OPC is one of many compositions in the Cao-SiO_2-Al_2O_3 system
- ‘by-product materials’ from other industries
- Clinker substiutes: fly ash, slag and limestone
- Reactivity and size



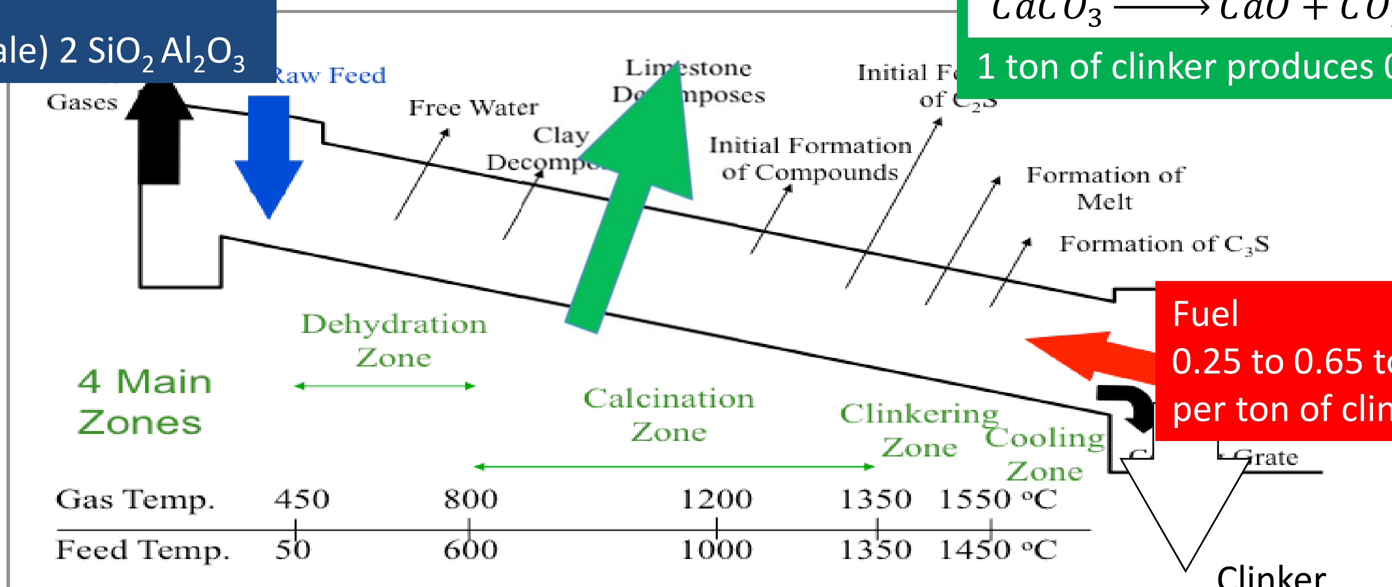
Ordinary Portland Cement

Limestone ($CaCO_3$)
Iron Oxide (Fe_2O_3)
Silica SiO_2
Aluminate (Clay, Shale) 2 SiO_2 Al_2O_3

Calcination

$$CaCO_3 \xrightarrow{\text{yields}} CaO + CO_2$$

1 ton of clinker produces 0.5 ton CO_2



Fuel
0.25 to 0.65 ton CO_2 per ton of clinker

Clinker
3 CaO SiO_2
2 CaO SiO_2
3 CaO Al_2O_3
4 CaO Al_2O_3 Fe_2O_3

Intergrind

Gypsum + Clinker
$CaSO_4$ $2H_2O$

Ordinary Portland Cement

Portland Limestone Cement

Limestone ($CaCO_3$)
Iron Oxide (Fe_2O_3)
Silica SiO_2
Aluminate (Clay, Shale) 2 SiO_2 Al_2O_3

Calcination

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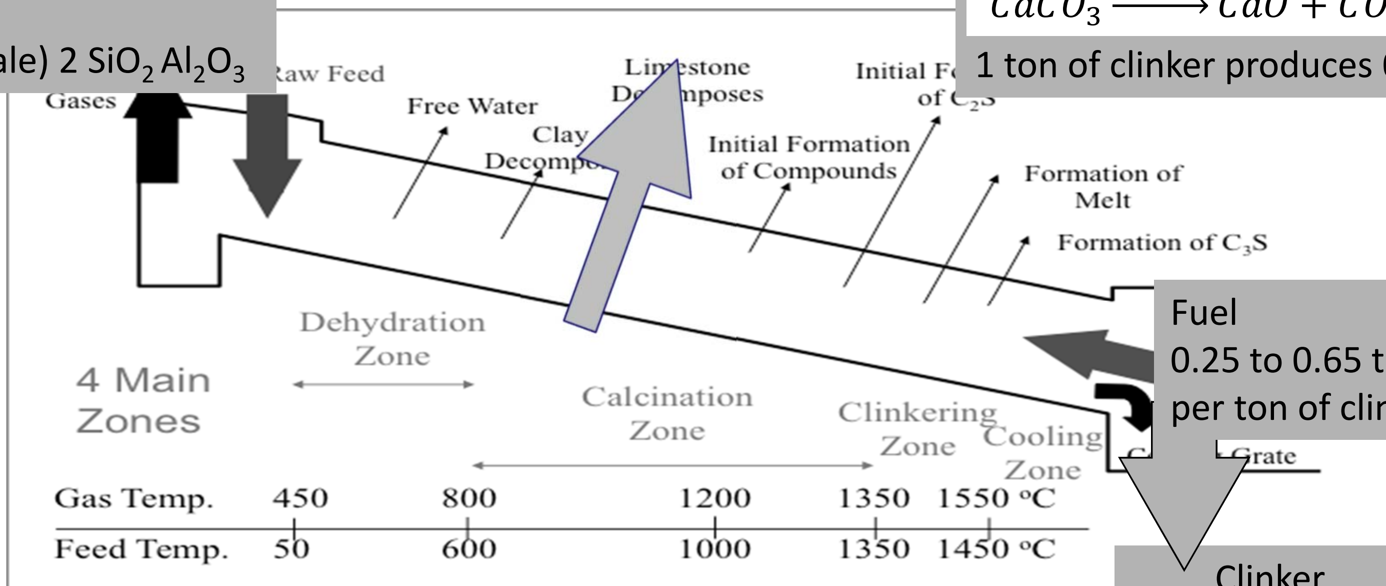


Fuel
0.25 to 0.65 ton CO_2
per ton of clinker

Clinker
3 CaO SiO_2
2 CaO SiO_2
3 CaO Al_2O_3
4 CaO Al_2O_3 Fe_2O_3

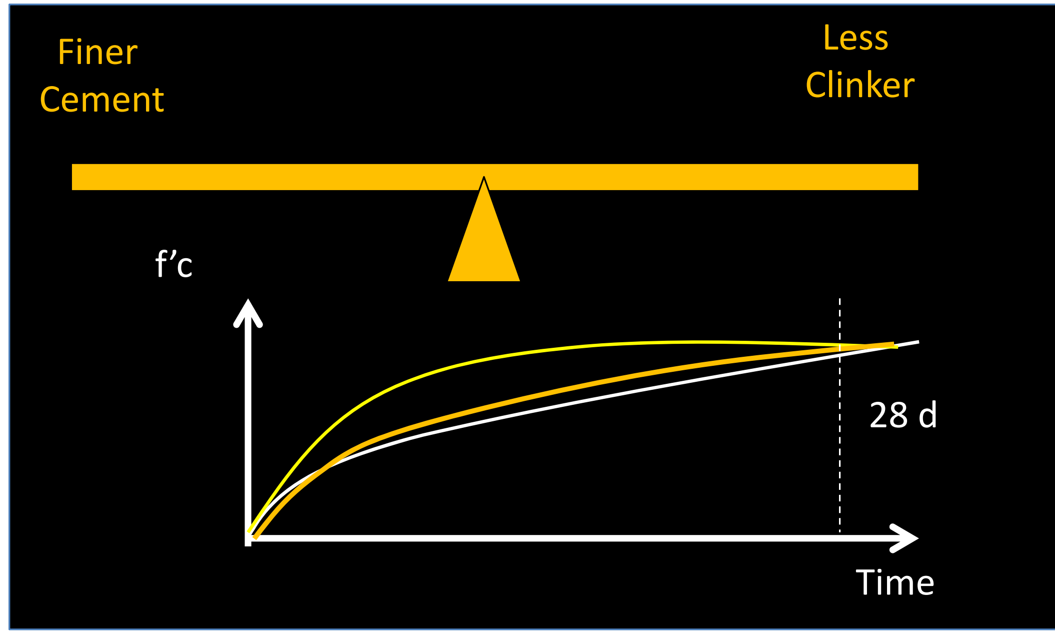
Intergrind

Gypsum + Clinker + Limestone
$CaSO_4$ $2H_2O$ $CaCO_3$

Portland Limestone Cement

Approach for Manufacture of Portland Limestone Cement

- Similar performance is targeted
- PLC is generally ground finer than OPC
  - PLC requires more grinding
  - Higher fineness may act as a nucleating agent to increase early age strengths
- Higher reaction rates may show benefits of blending with other supplementary materials
- Finer cements can show higher shrinkage & cracking potential



A Comment on Grinding

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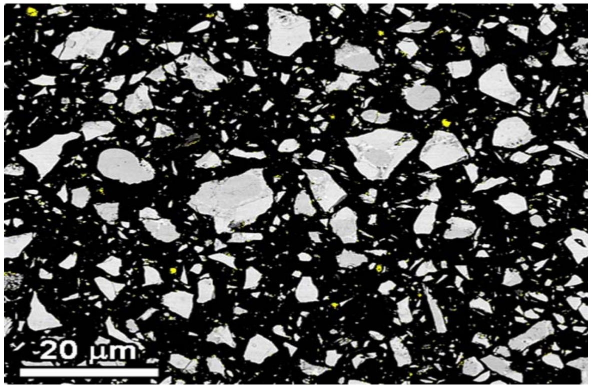
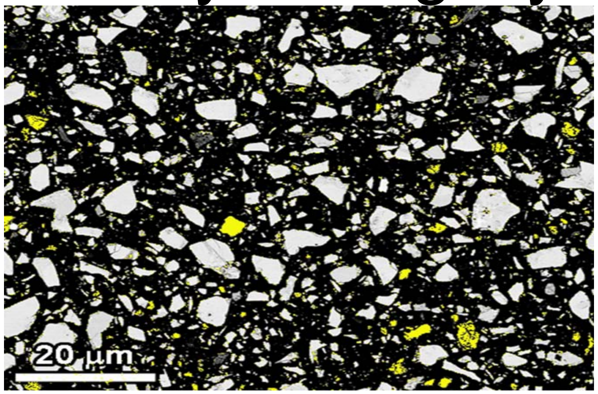
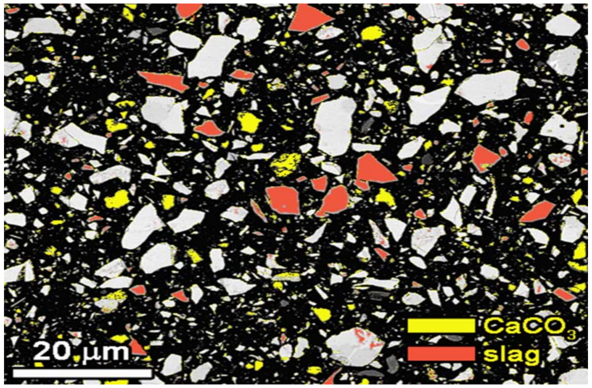
- Blaine fineness typically increased to compensate for lower clinker content (8 to 10 m^2/kg per % of LS added
- generally 80 to 100 m^2/kg to go from OPC (2%) to PLC (12%)
- Interground limestone is very fine since limestone is softer than clinker, the clinker may be slightly finer







PLC Performance Studies

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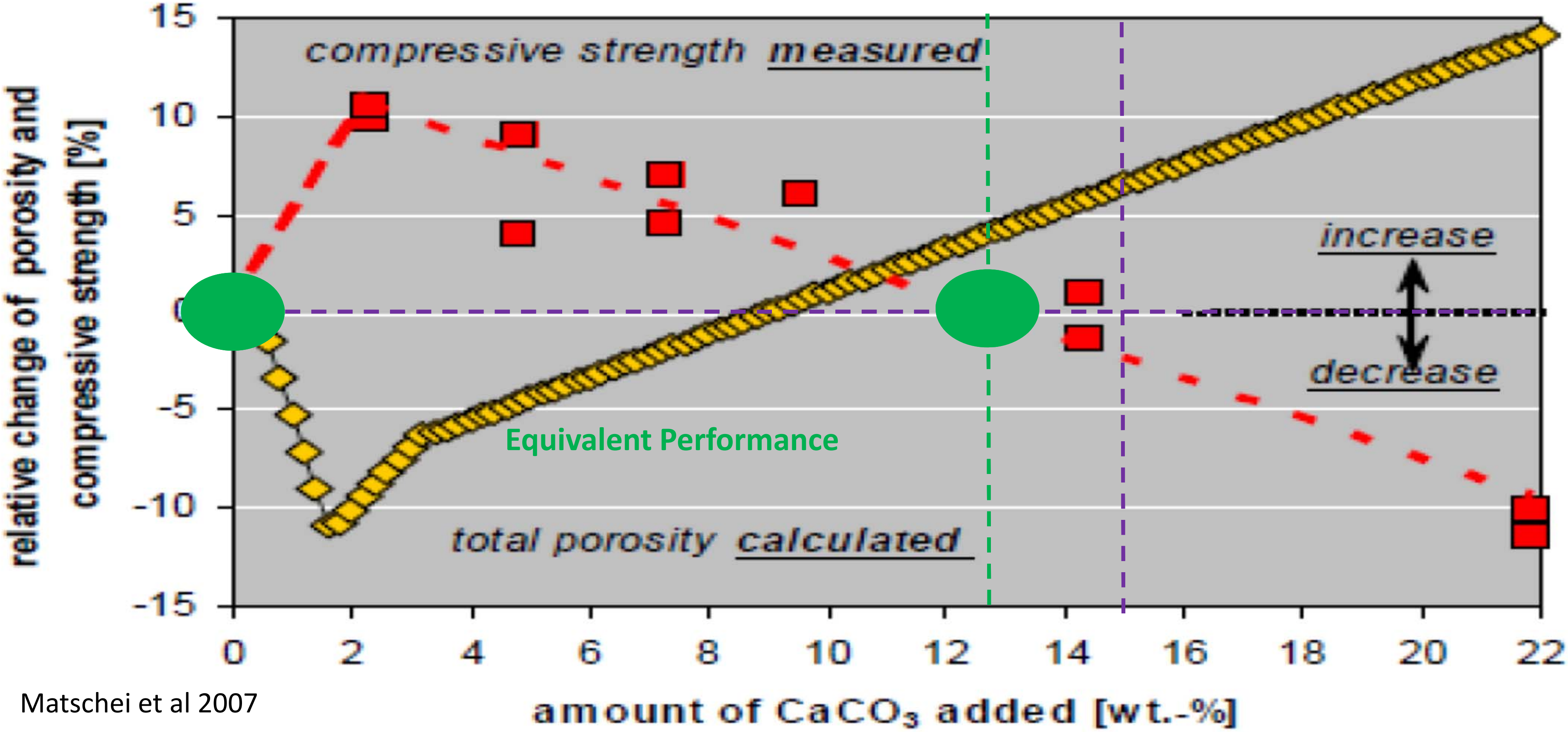

Matschei et al 2007

Field Trials – Barrier Walls (Hooton 2009)

Oregon State University College of Engineering

- Minor scaling where water collects
- GU, GUL, GU, and GUL Slag
- Also used in paving operations

23 m^3 of each mix placed, 30 MPa, 60-100 mm (2.5-4 in.) slump

Nov. 2009 Barrier Wall

2009 Barrier Wall	PC +25% SLAG	PLC + 25% SLAG
Shrinkage (28d)	0.038%	0.038%
Strength (MPa)		
1	9.5	10.3
3	19.3	19.4
7	25.6	26.8
28	36.9	37.9
56	38.9	38.0
91	40.7	40.2
Freeze/Thaw Durability	94%	94%
MTO LS-412 Scaling	0.24 kg/m^2	0.24 kg/m^2
RCP (Coulombs)		
28 days	2070	1490
56 days	1930	1340

Interesting Observation

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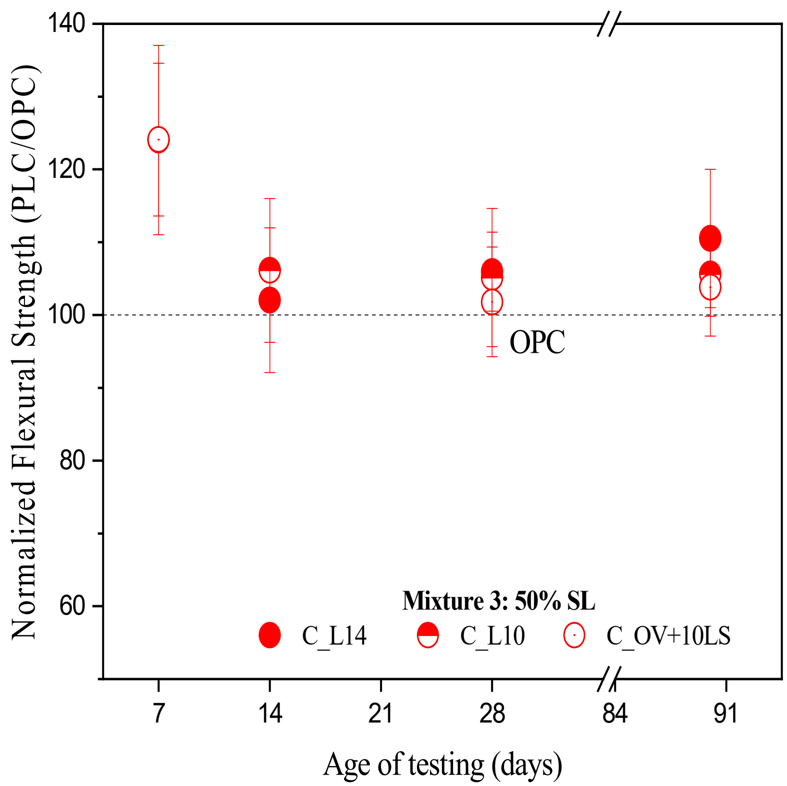
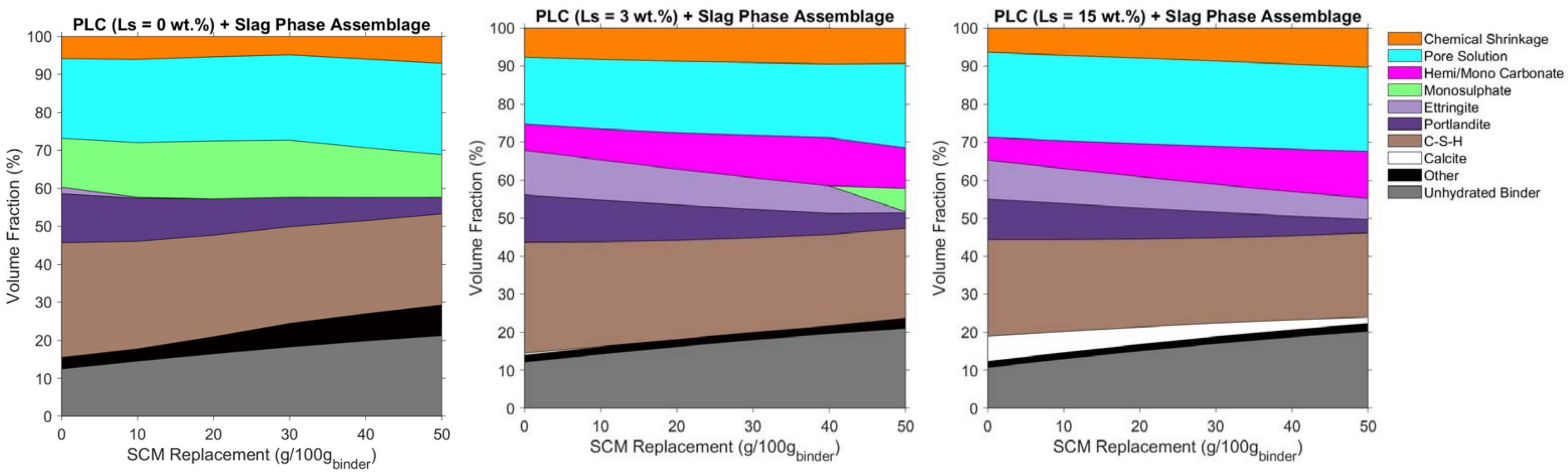


- When slag is used with PLC the early strength (and overall strength) tend to increase

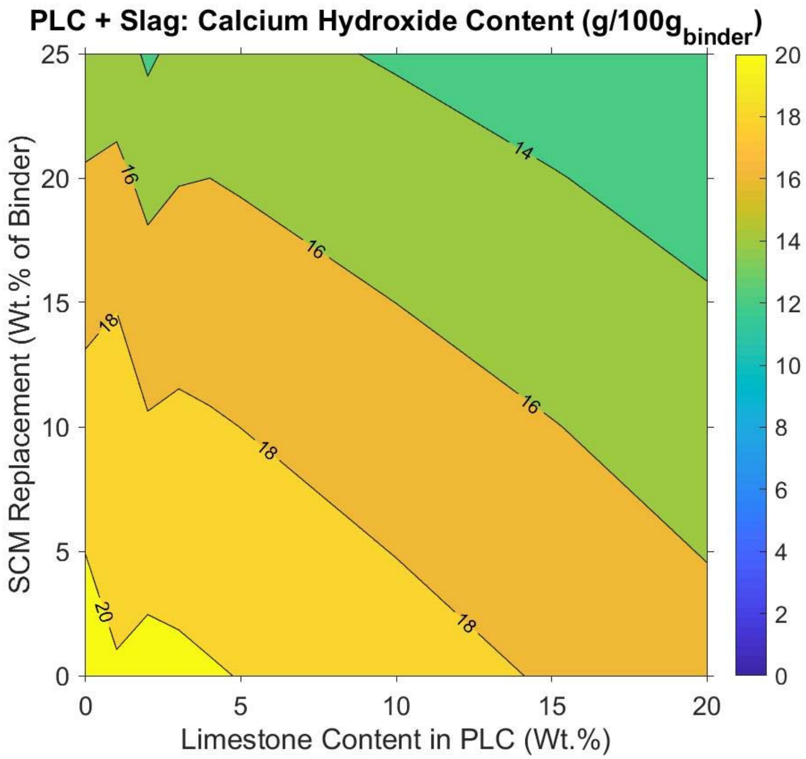
- This is due to a synergistic effect of the limestone with slag

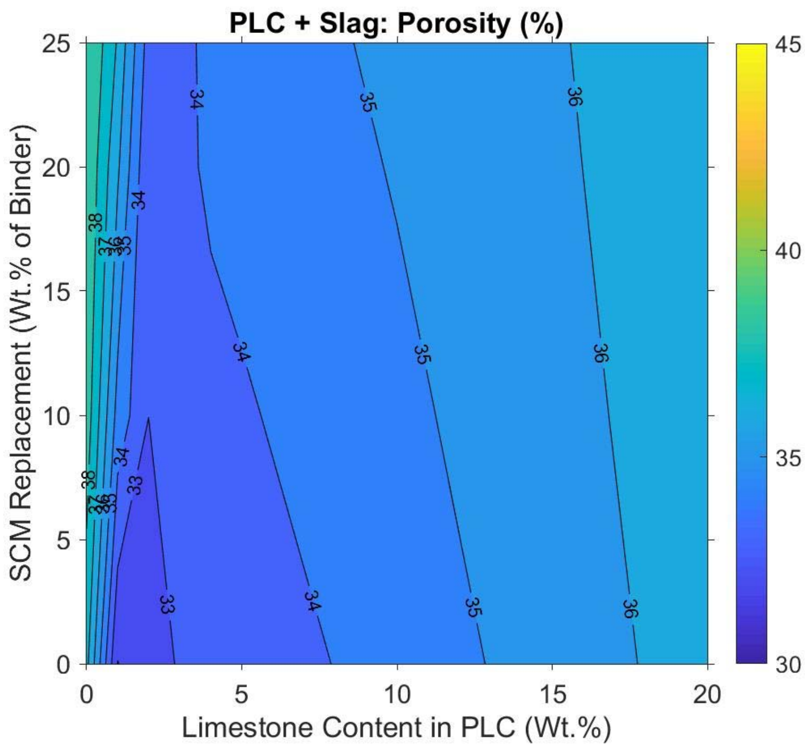
Thermodynamic Model

- As limestone is increased, the chemical shrinkage increases and the monosulfate converts to ettrinigte and hemi/mono carbonate



PLC + Slag


PLC + Slag: Calcium Hydroxide Content (g/100g$_{binder}$)
SCM Replacement (Wt.% of Binder)
Limestone Content in PLC (Wt.%)
0
5
10
15
20
25
14
16
18
20

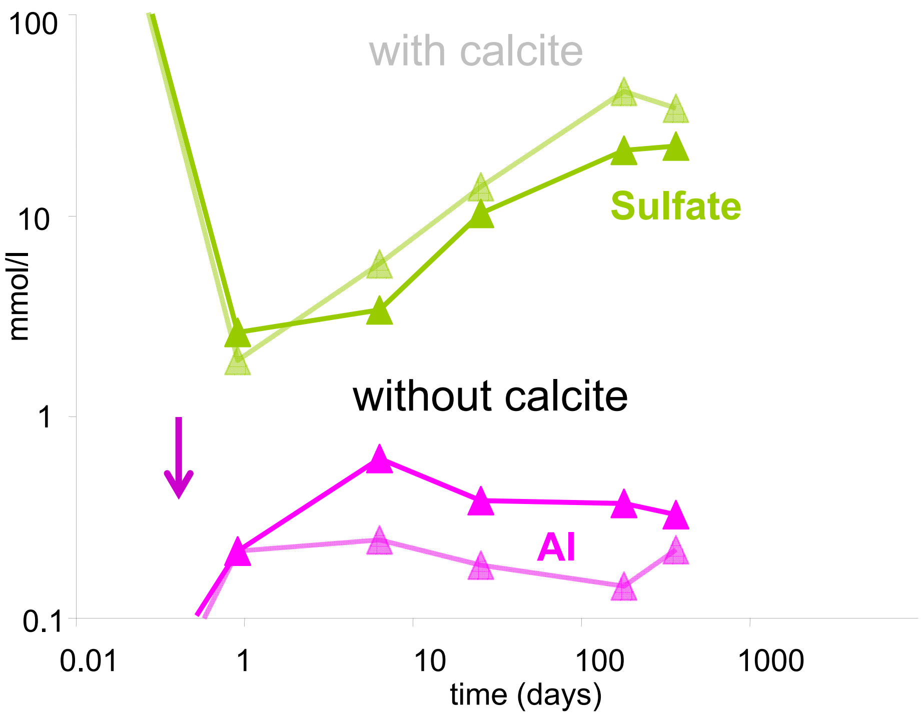

PLC + Slag: Porosity (%)
SCM Replacement (Wt.% of Binder)
Limestone Content in PLC (Wt.%)
0
5
10
15
20
25
30
33
34
35
36
37
38
40
45

Effect of limestone on pore solution (From Lothenbach)

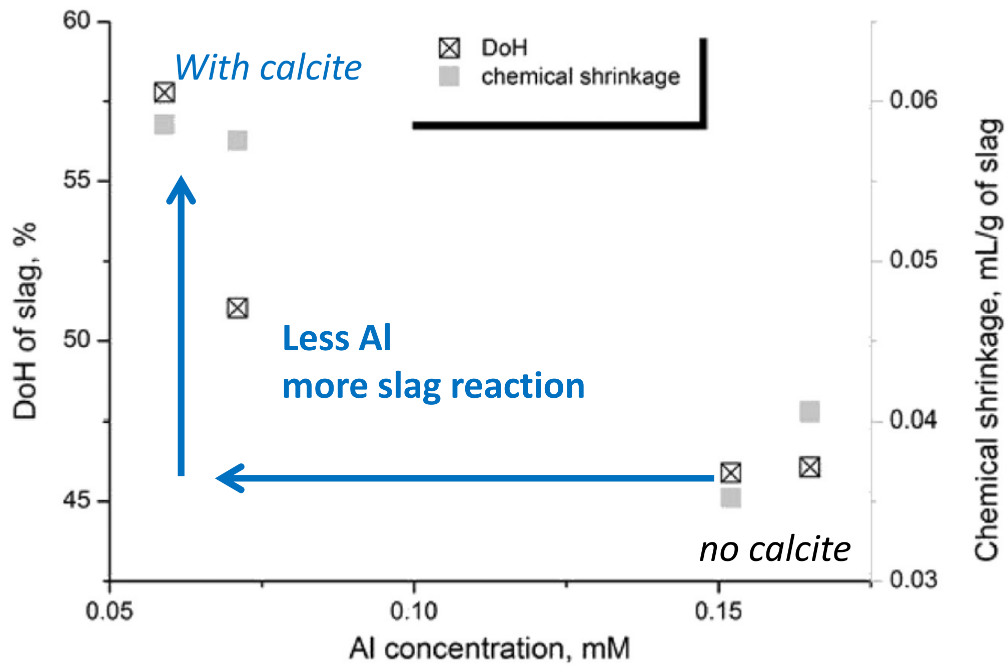
Days to years:

Limestone lowers aluminium concentrations

Faster slag reaction



Lothenbach et al. 2008, CCR 38



Adu-Amankwah et al. 2017, CCR 100

Conclusions

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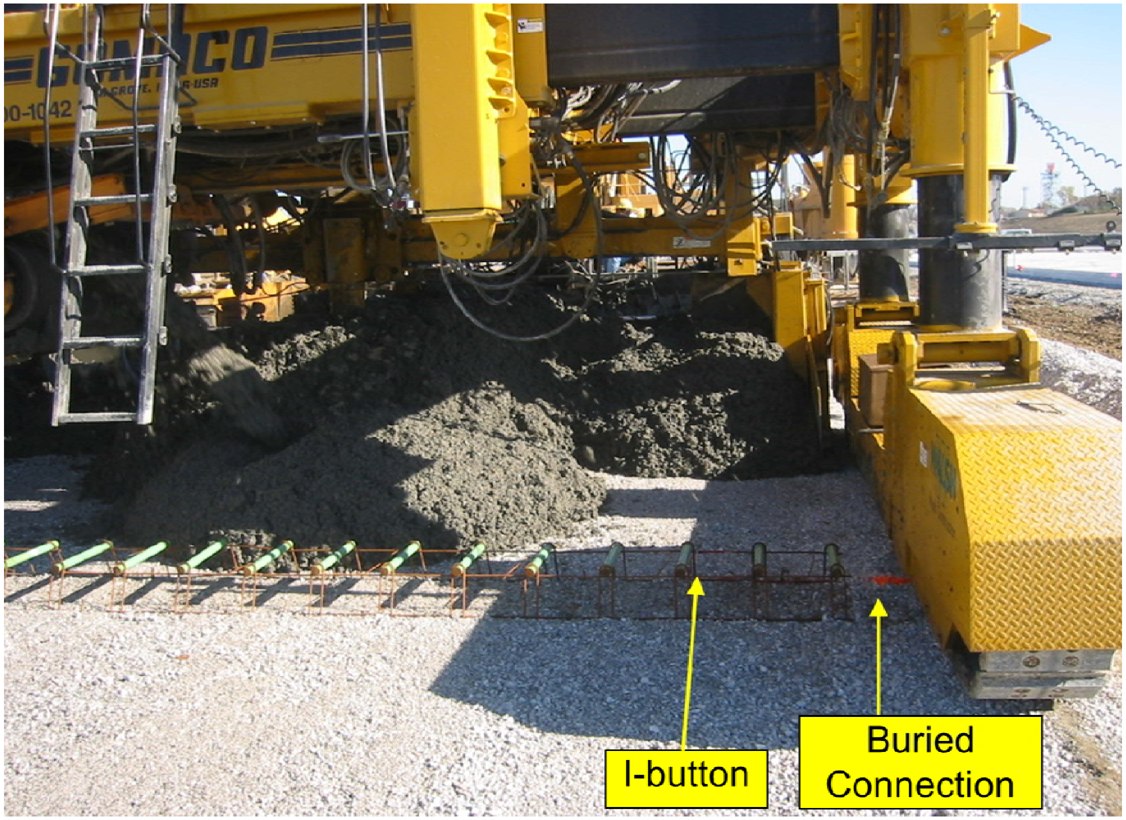
- Salt damage occurs at joints in pavements due to calcium oxychloride formation
- Slag reduces the potential for damage to occur – Dilution and reduction in CH
- New reactivity test (the pozzolanic test needs interpretation for non pozzolans)
- LTDSC Test is very useful
- Thermodynamic modeling is very useful
- Limestone and slag are a great combination

Concrete at Early Ages: Relating Science and Construction Operations

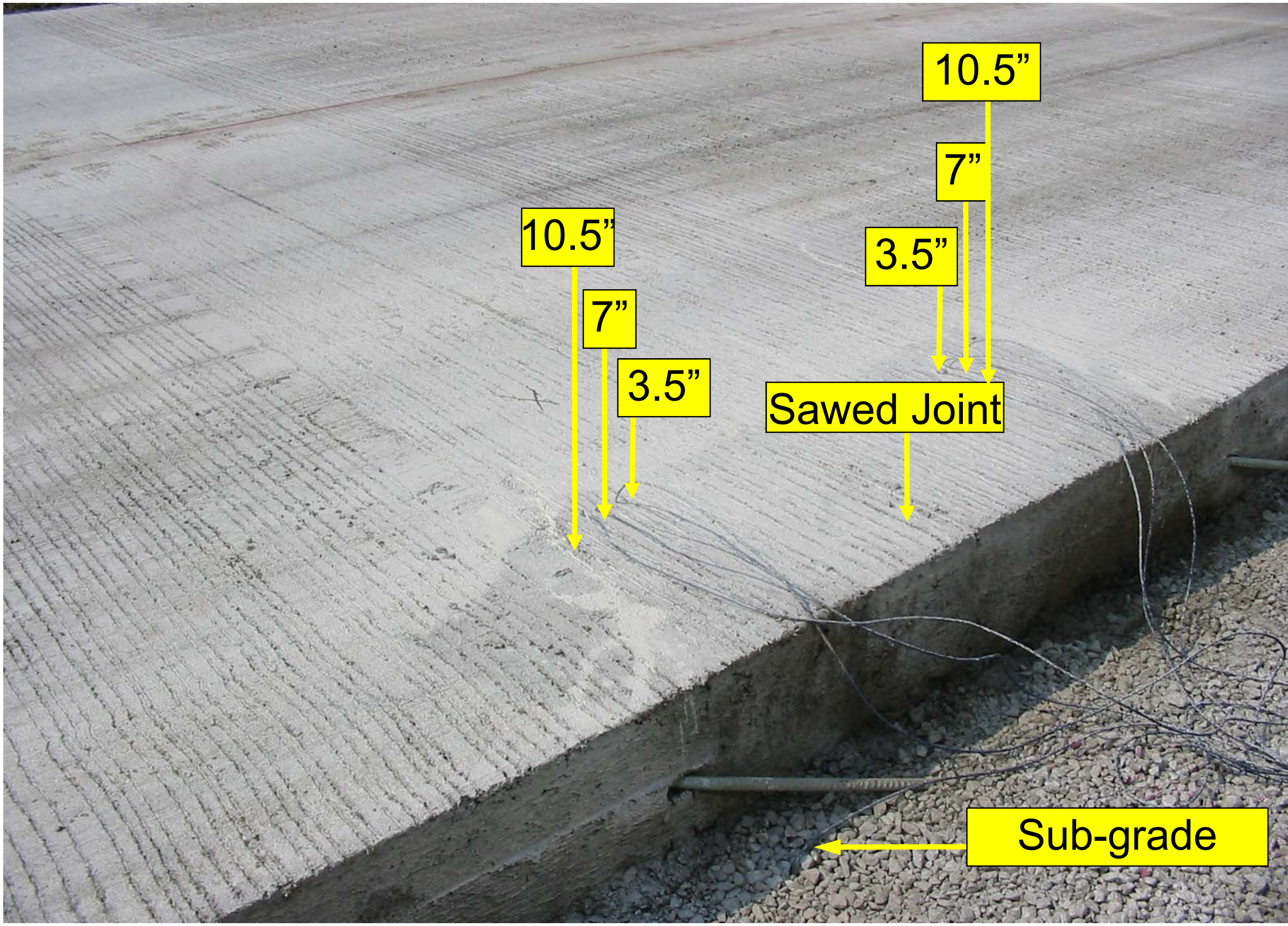
Construction Operations

- procedure for determining the appropriate saw-cutting time window constructed under the range of environmental conditions
- appropriate depth of the saw-cut that minimize the risk of damage (micro-cracking) and random crack development, and
- Developed tools and training materials



Field Work

- 5 site visits (4 locations)
- Wide range of envir. (81ºF -24º)
- Night pave
- 3 different mix design
- 10”, 12”, 14” and 15” pavement



Modeling Approach

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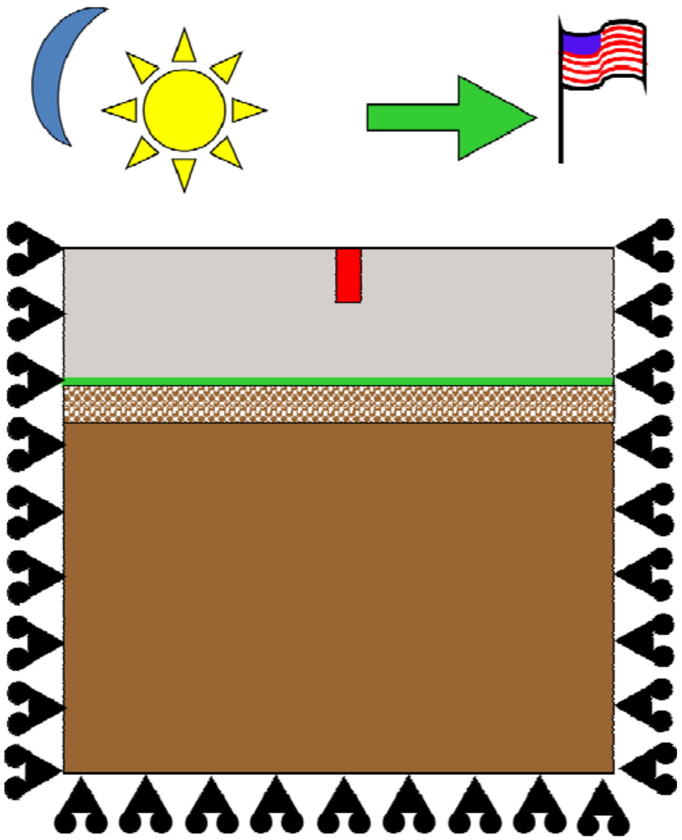
- Model developed to simulate stress and strain development in concrete pavements (slabs, decks) at early ages
- Model considers material properties, environmental exposure, and can introduce the sawcut



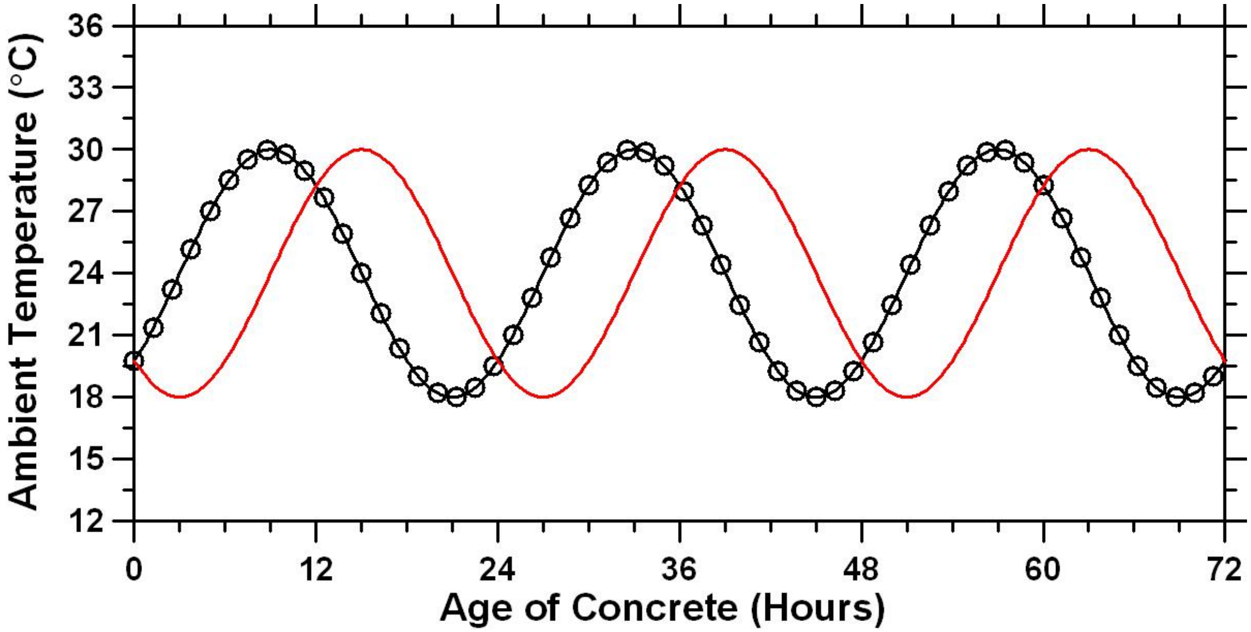
The concrete mixture we are simulating is close to the mixture used by Berns Const.

w/cm = 0.42
air = 6.5%
Initial temp = 20ºC
*** can be varied**

Ambient Temperature

Oregon State University College of Engineering

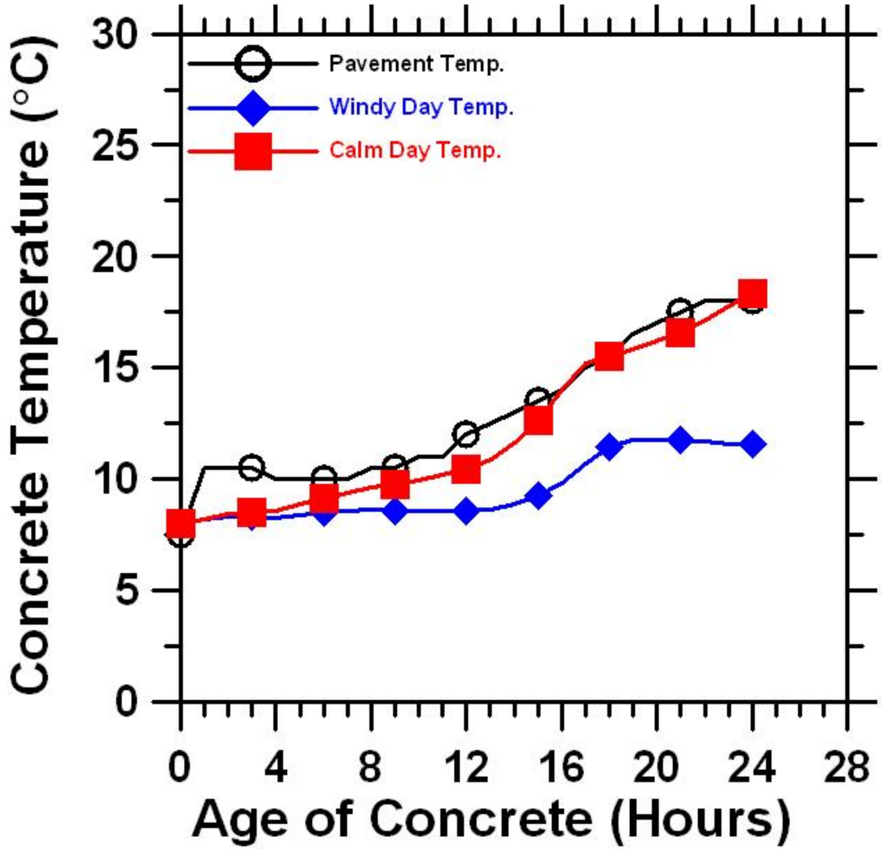
- **Choice of constant, periodical and linear ambient temperature functions**
- **This temperature function can be shifted to the right or to the left to consider paving operation at different times of the day**



Temperature fluctuates between 18 °C and 30°C in a 24 hours time period

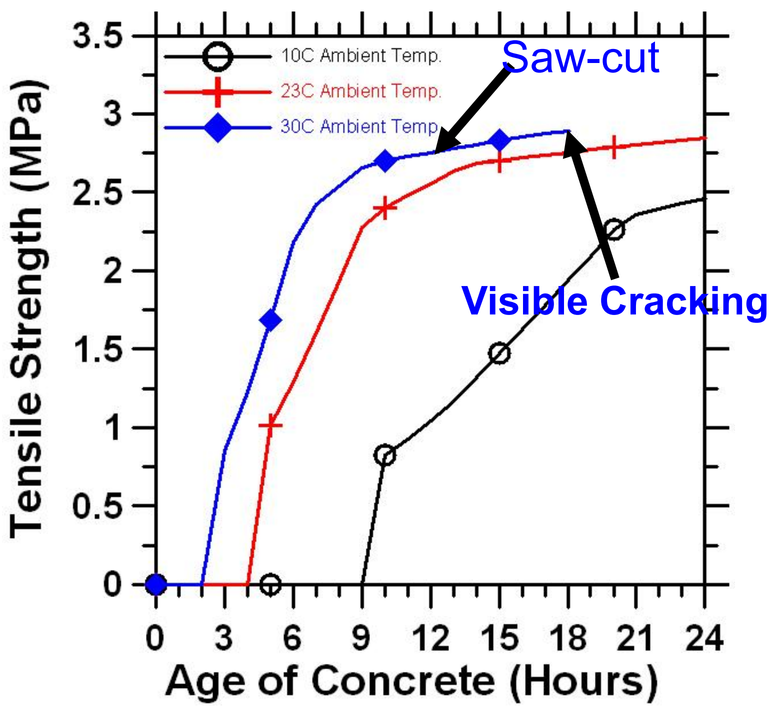
Influence of the Wind

- Analysis shows that the higher the wind velocity, the higher the rate of heat dissipation, the lower the concrete temperature.
- The results compare well with field measurements.



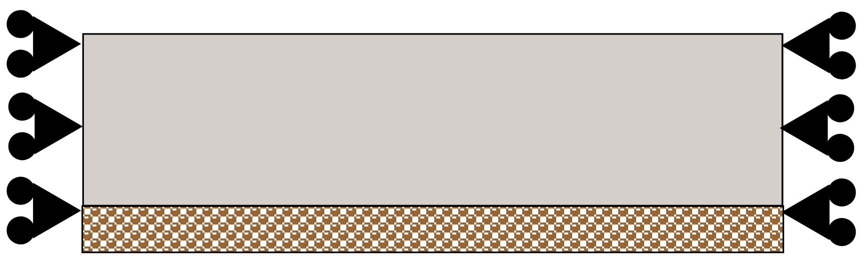
Influence of Ambient Temp. on Property Dev.

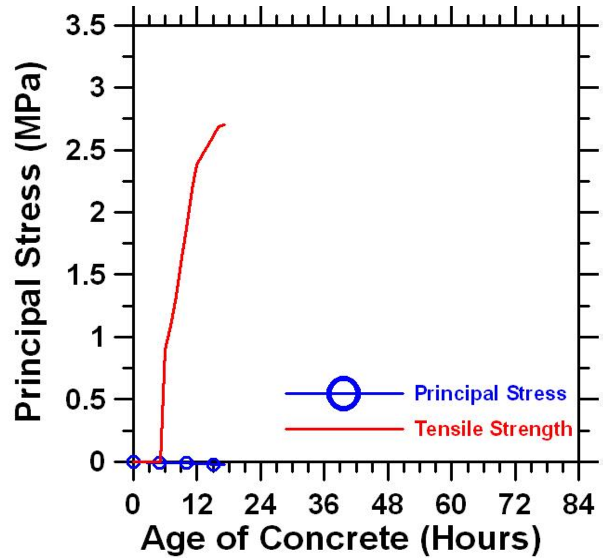
- 3 simulations performed with constant 10°C, 23°C, 30°C ambient temperatures
- As an example, tensile strength was measured at the tip of the notch
- Analysis reveals that the higher the ambient temperature, the higher the rate of concrete property development.

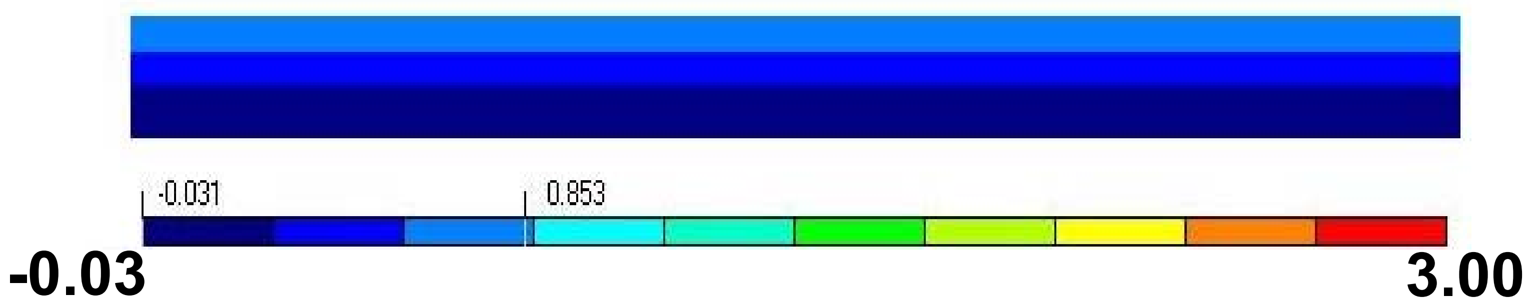


What Happens When There Is No Saw-cut ?! Case I

Step 1, 0–17 hours

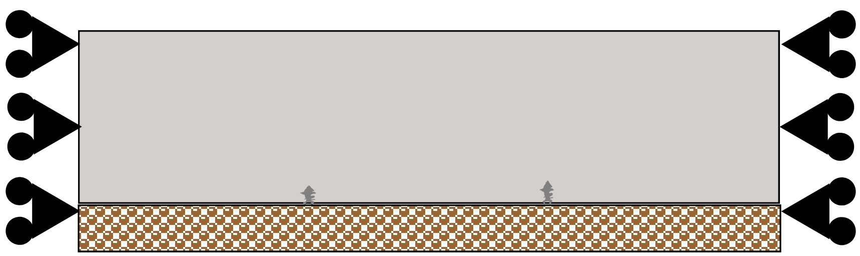


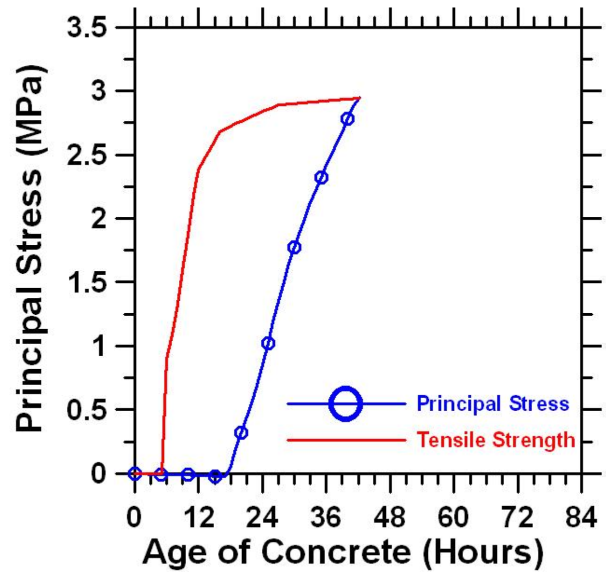


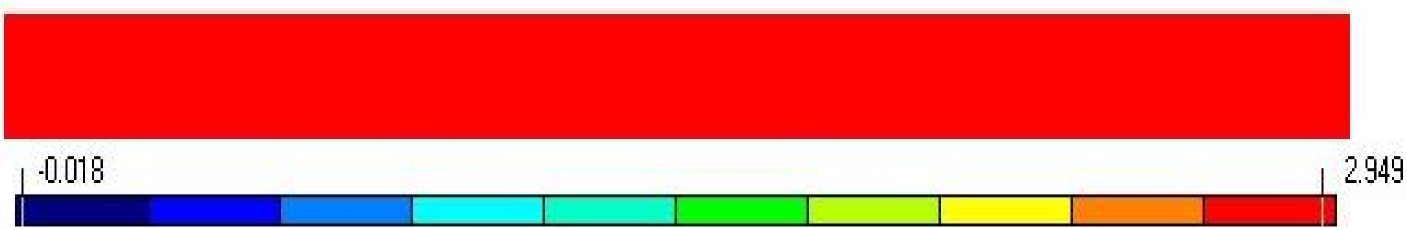


What Happens When There Is No Saw-cut ?! Case I

Step 2, 18-42 hours



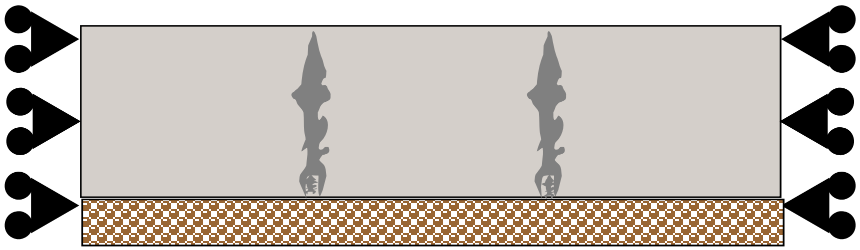


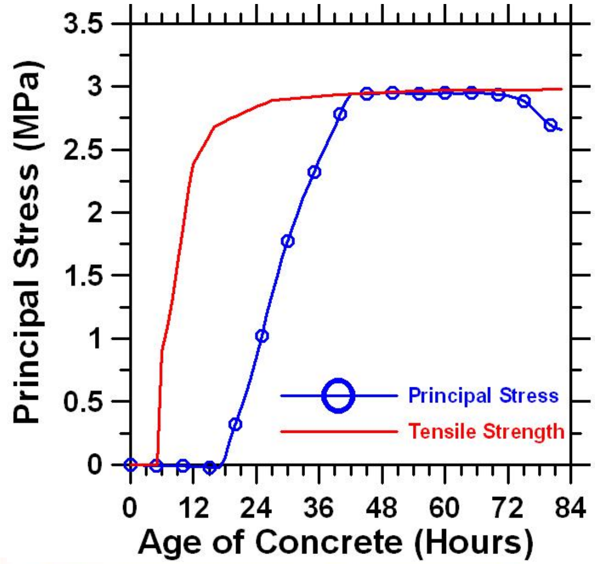


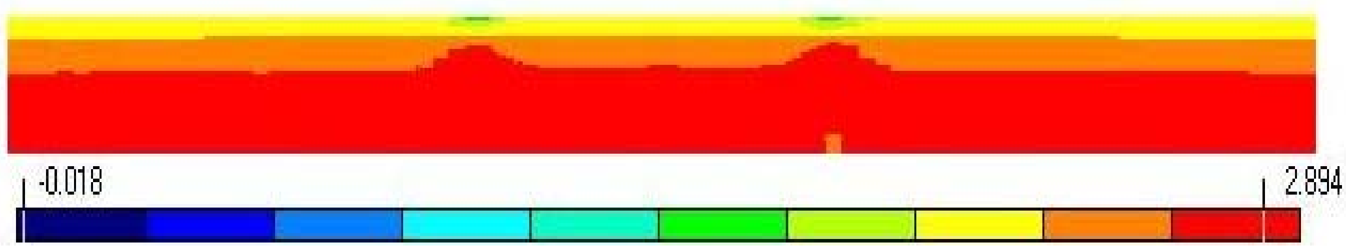
-0.03 **3.00**

What Happens When There Is No Saw-cut ?! Case I

Step 3, 43-82 hours





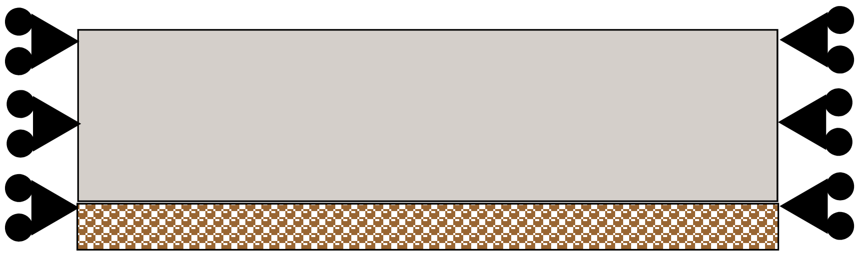


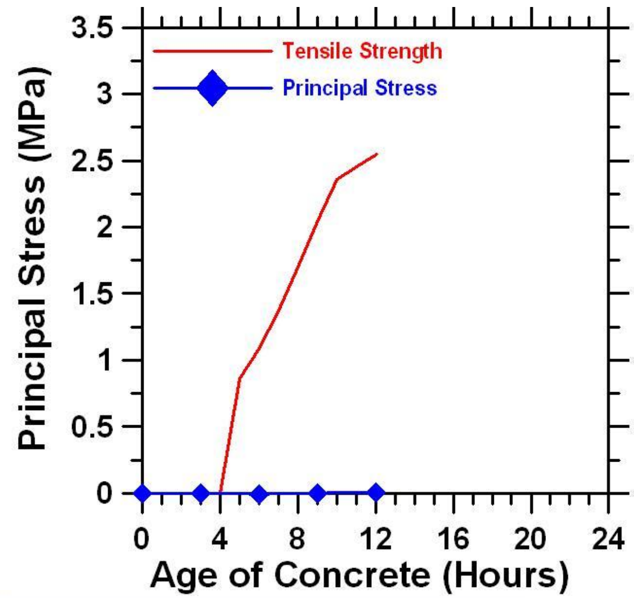
-0.03 **3.00**

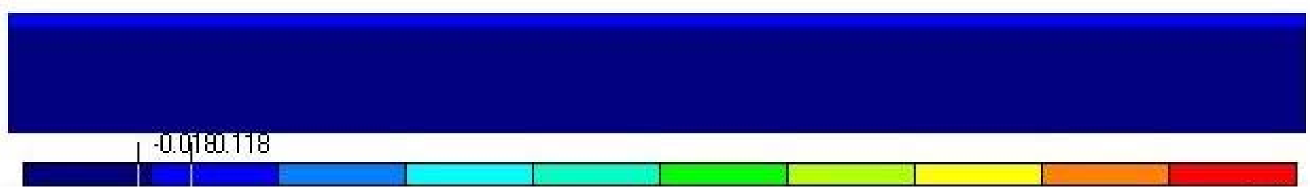
a_0= D/3 Notch Exerted at 12 Hours

Case II

Step 1, 0–12 hours





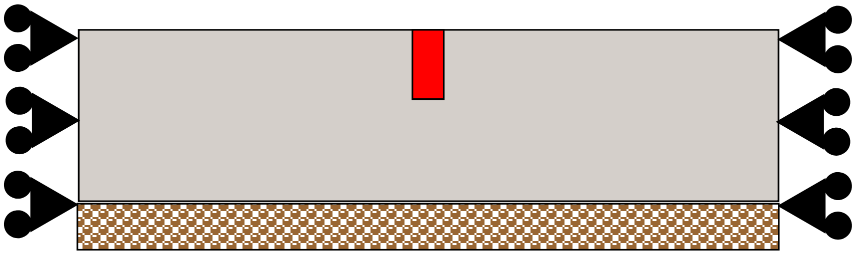


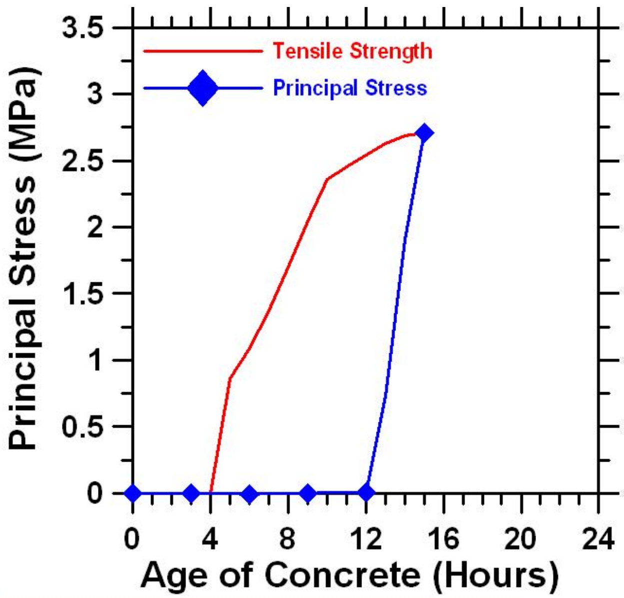
-0.30 **2.85**

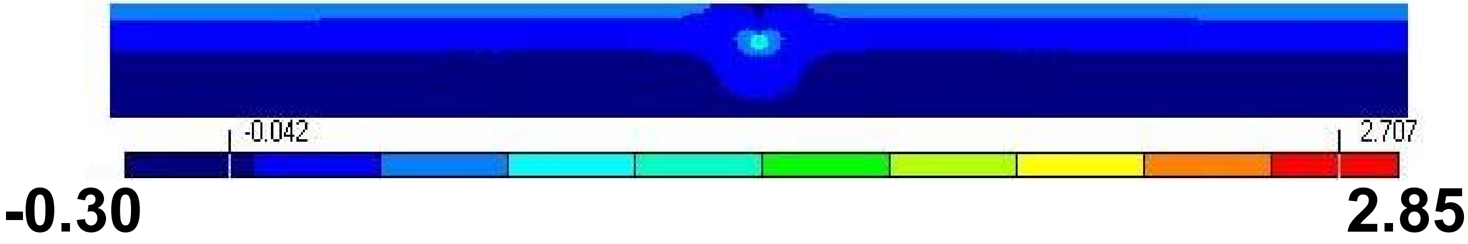
a_0= D/3 Notch Exerted at 12 Hours

Case II

Step 2, 13-15 hours

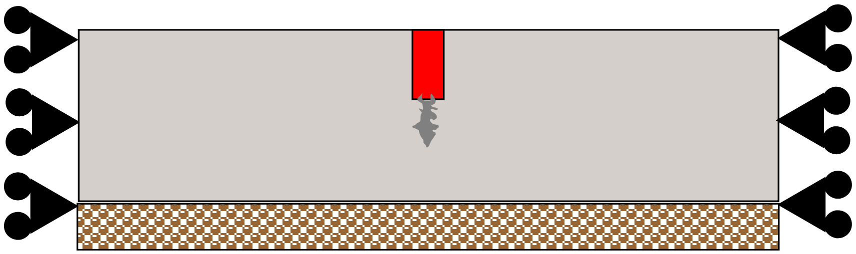


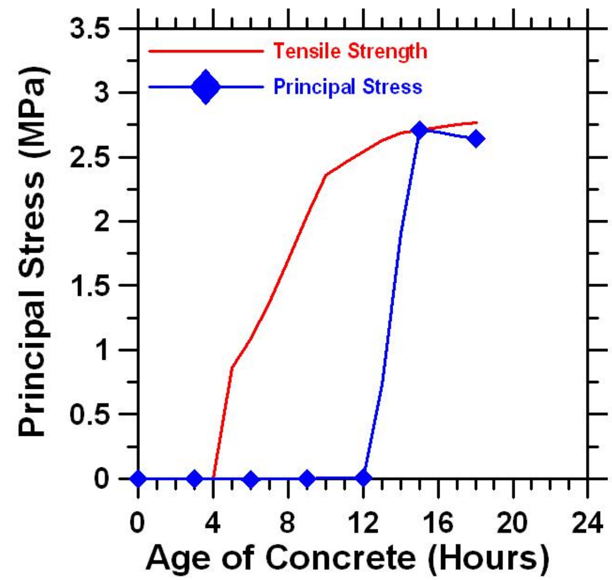


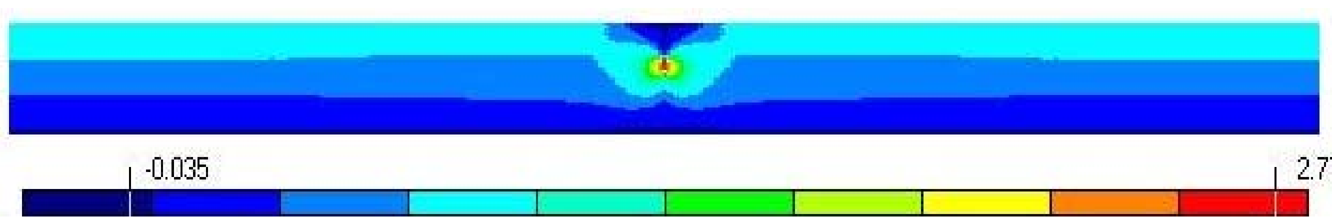


a_0= D/3 Notch Exerted at 12 Hours
Case II

Step 3, 16-18 hours

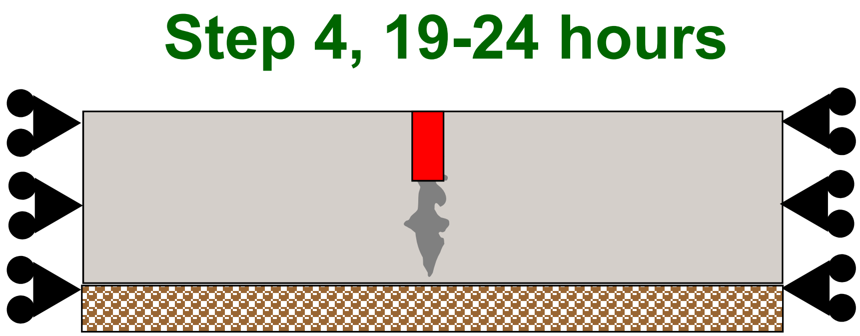


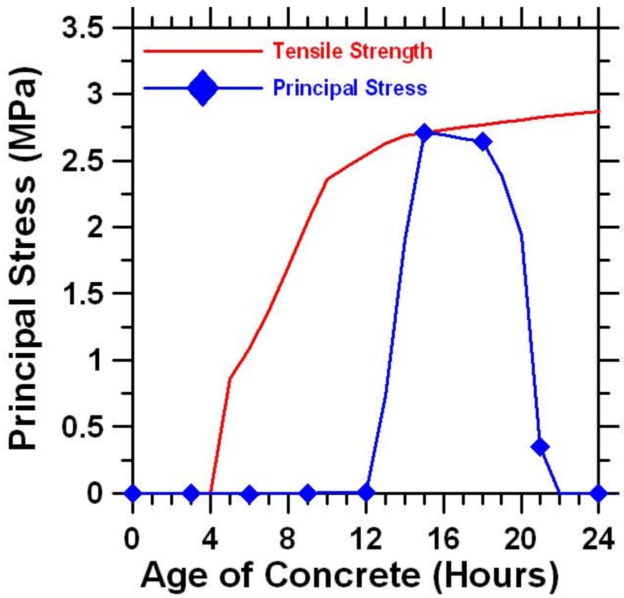


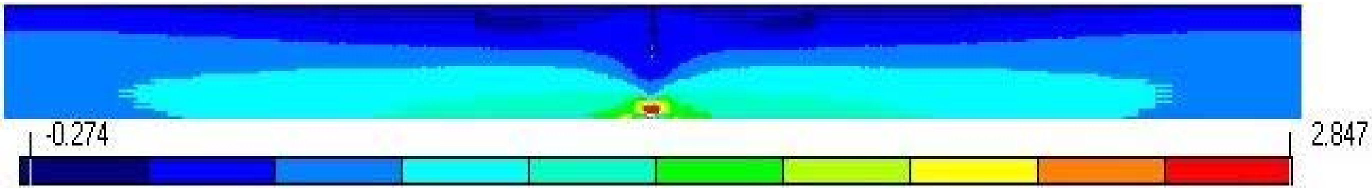


-0.30 **2.85**

a_0= D/3 Notch Exerted at 12 Hours
Case II



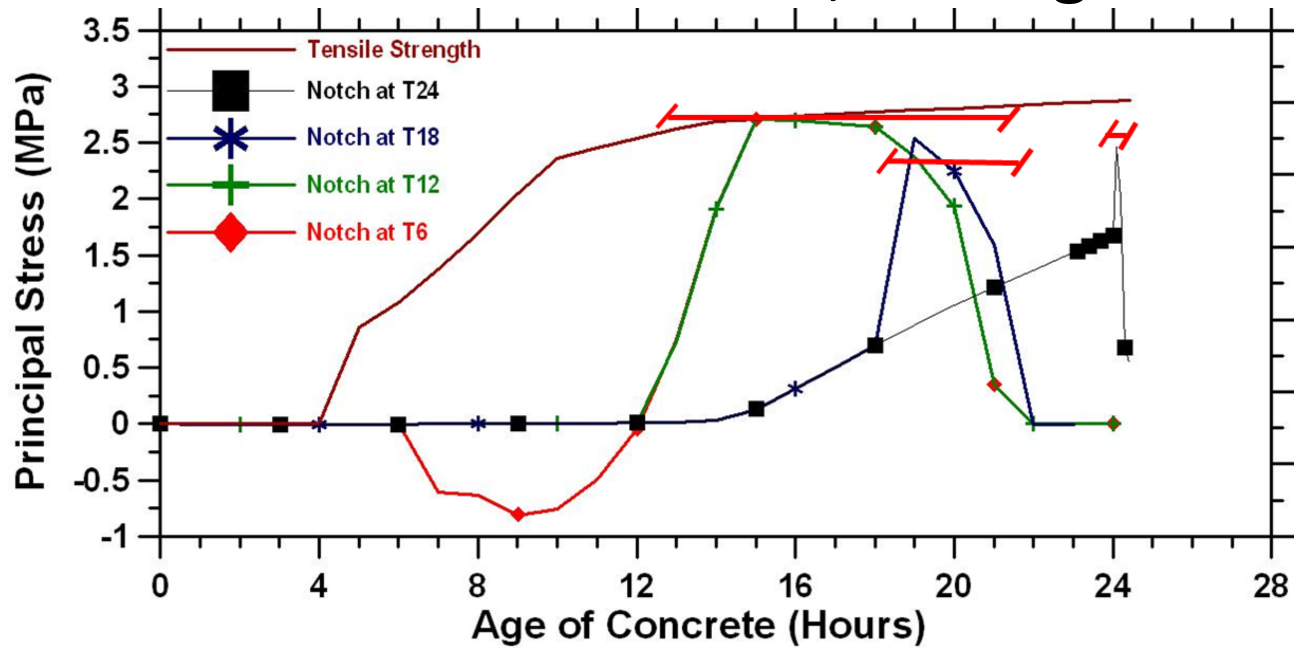




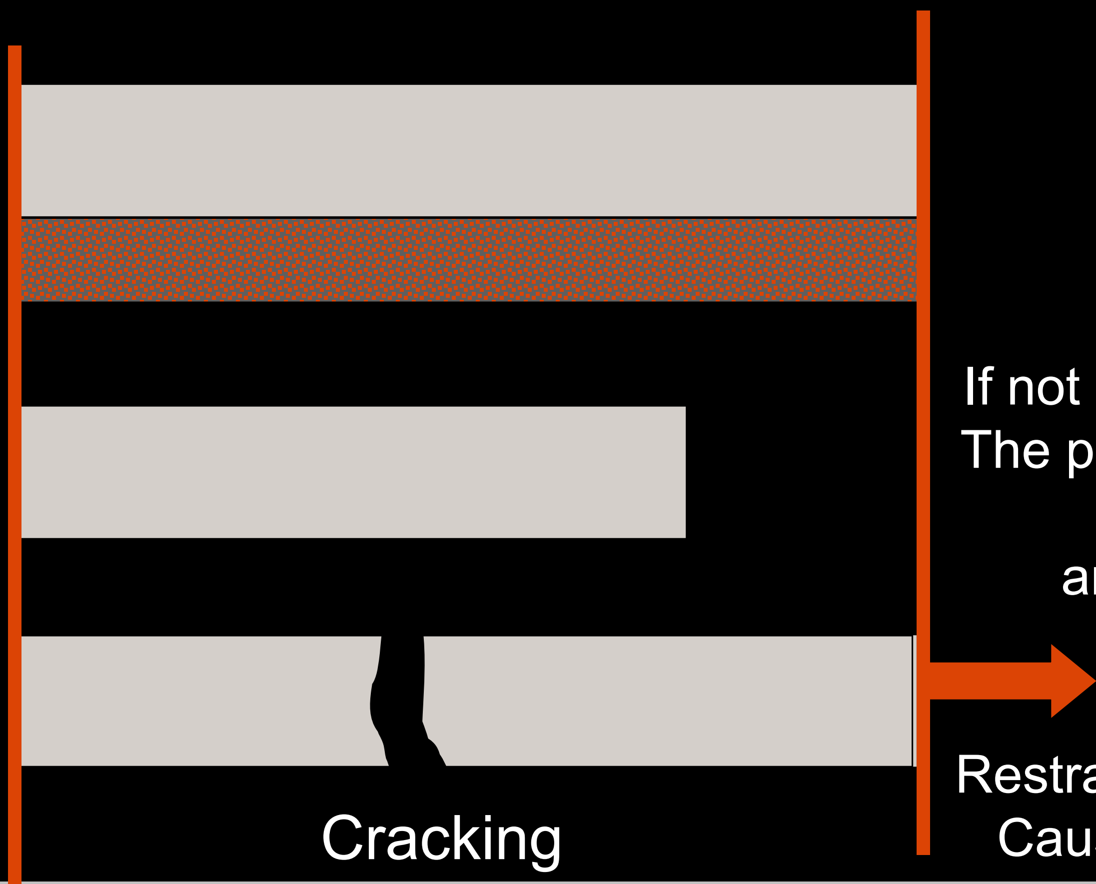
-0.30 **2.85**

Summary of Different Saw-cutting Time

- As shown in the graph, the later the notch is introduced, the more brittle the concrete, the higher internal stresses, the higher the potential for random cracking



Restrained Slab at Early Ages

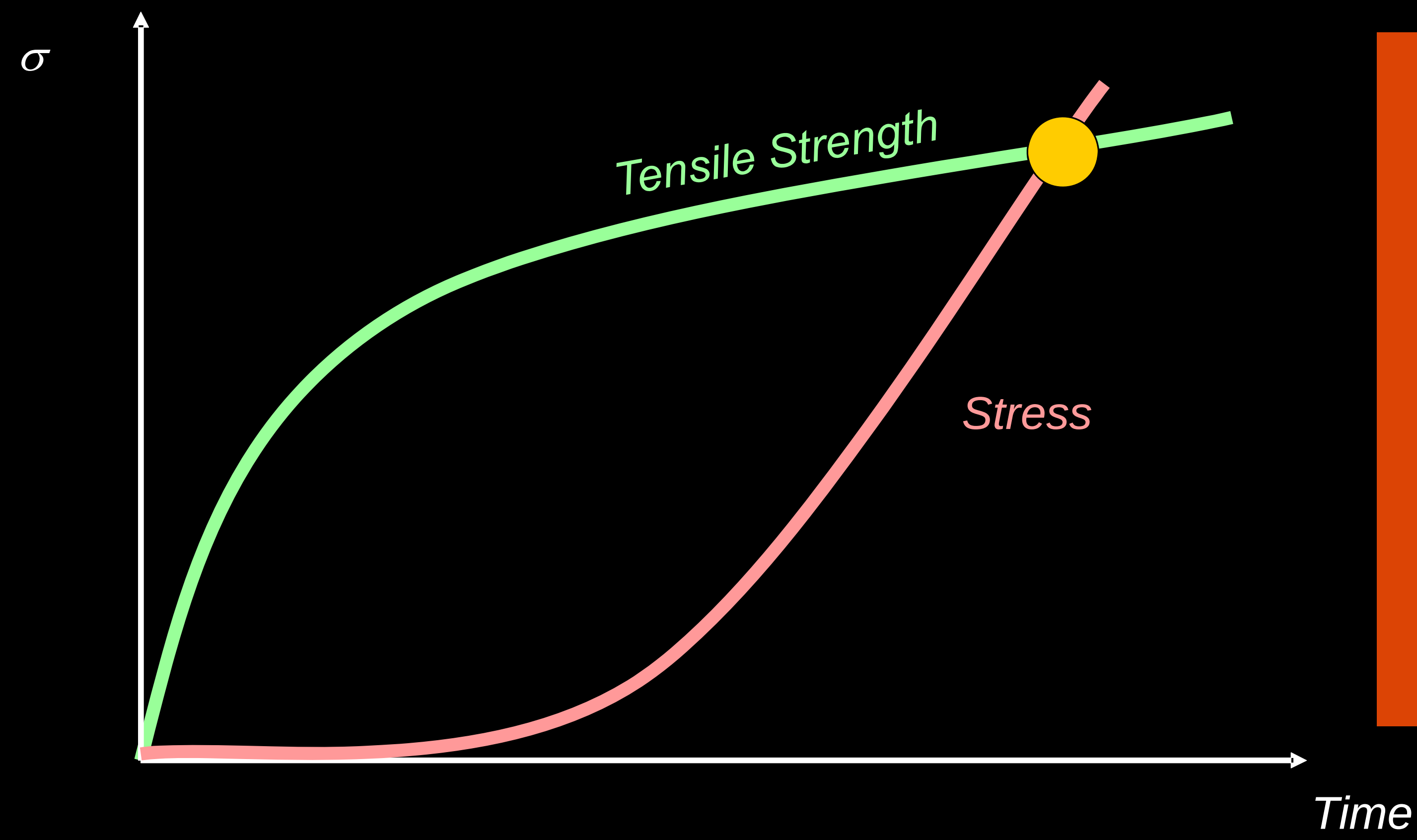


Initial Concrete

If not connected to the subgrade
The pavement would shrink due
to chemical reaction
and temperature change

Restraint 'pulls' on the concrete
Causing it to go into tension

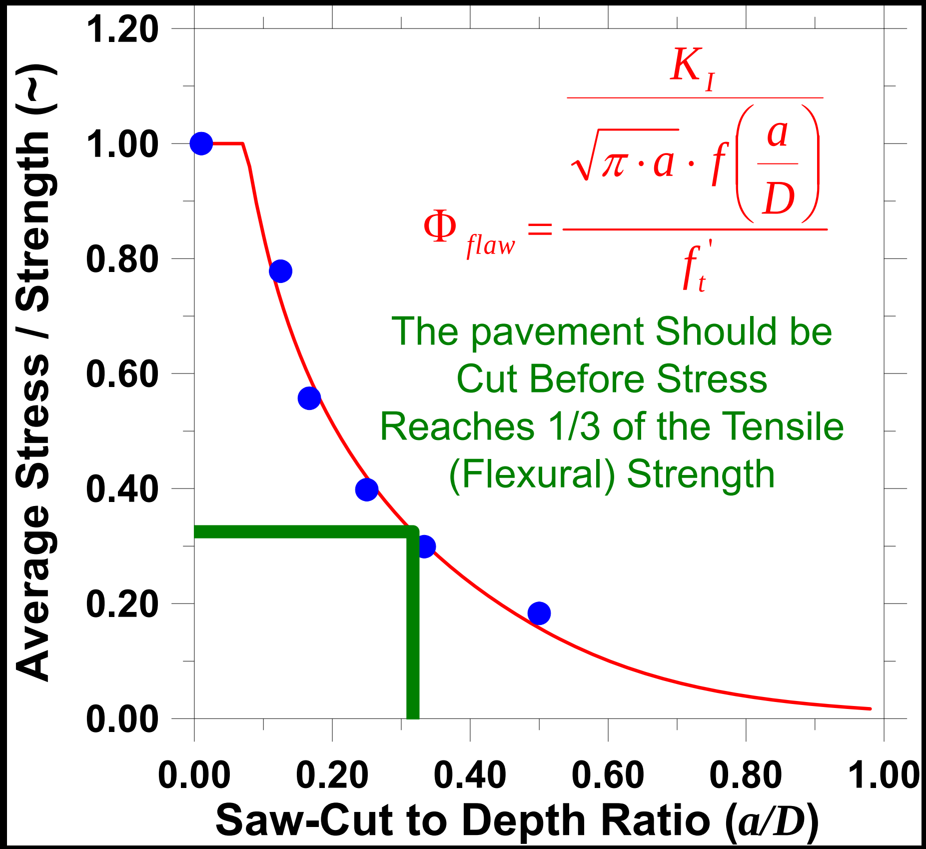
Comparing Stress and Strength



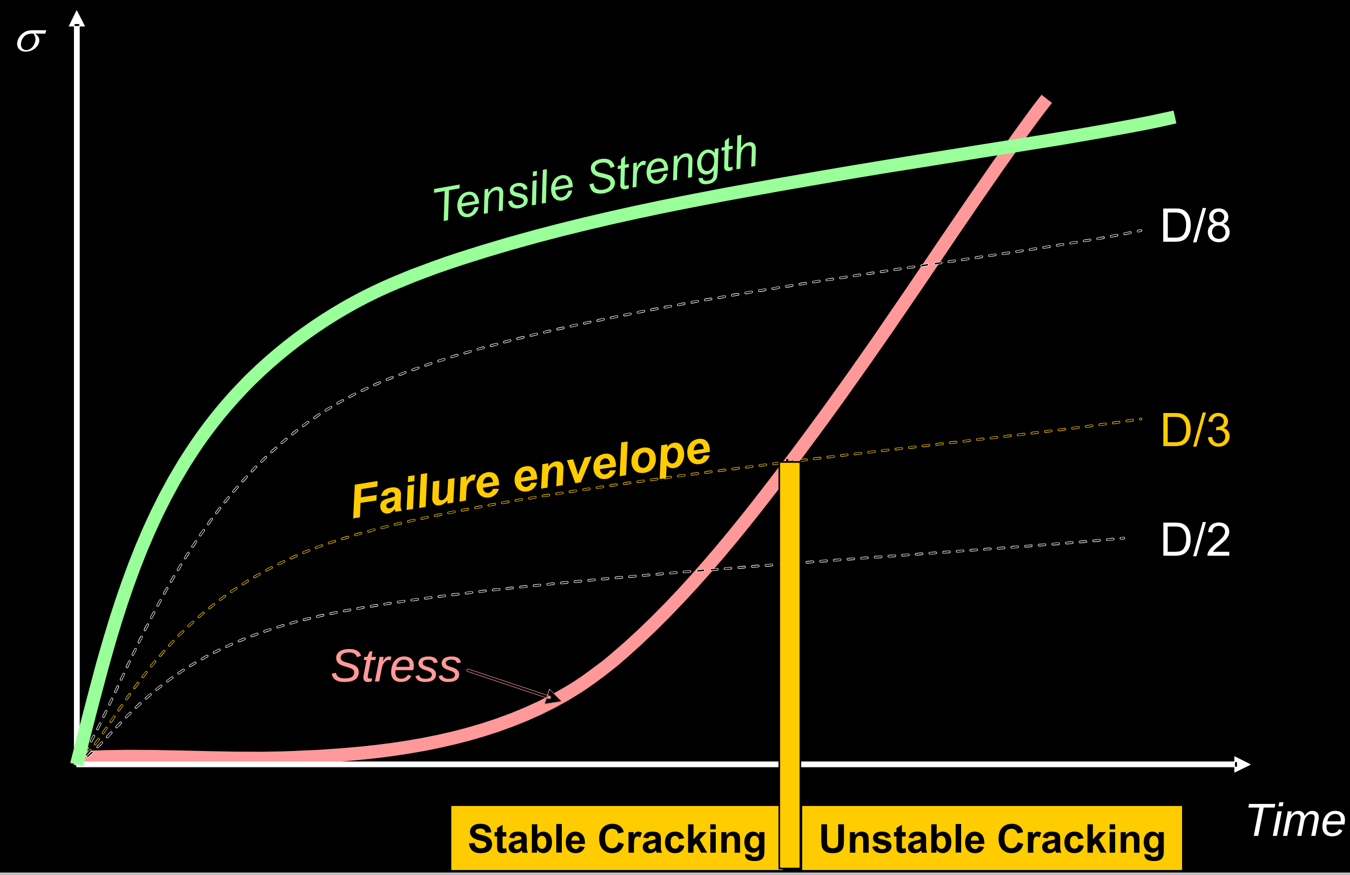
Valid for an Unnotched Specimen Only A Strength Reduction Factor is Needed for Cut Slabs

Saw-Cut Depth and A Strength Reduction Factor

- Average stress/ strength ratio for different saw-cut depths
- It can be used effectively to select appropriate depth of saw-cut



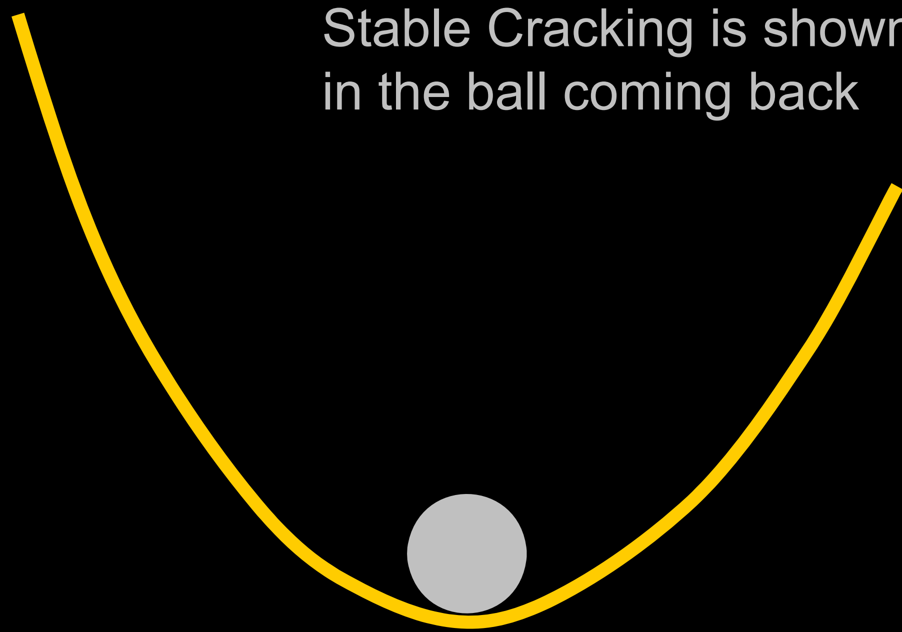
Comparing Stress and Strength When a Cut Exists



Stable vs. Unstable Cracking

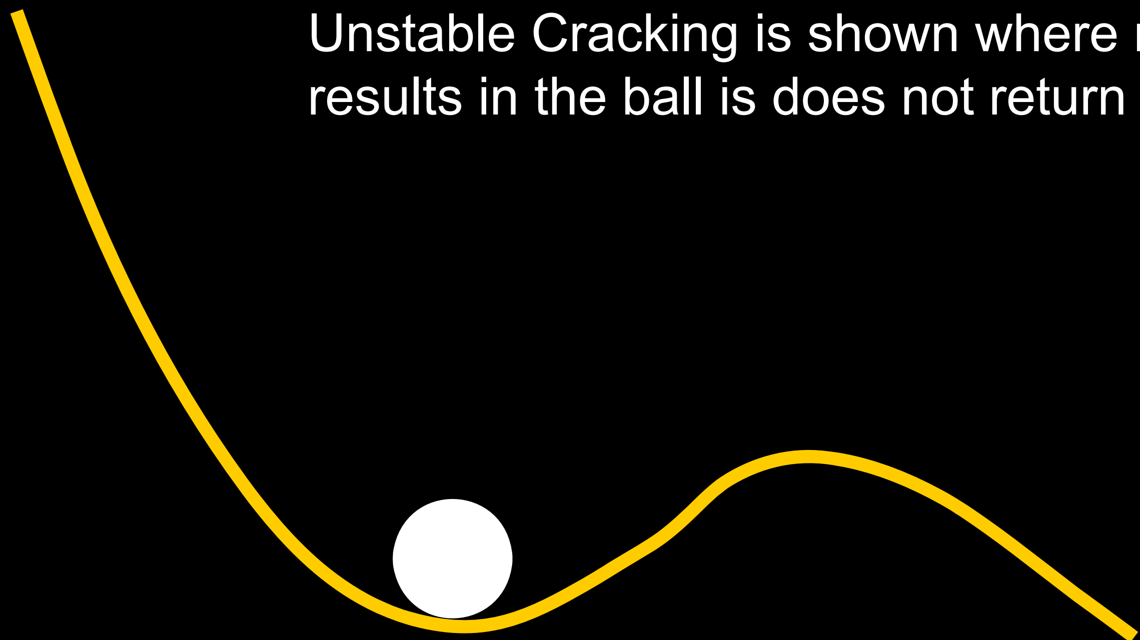
Sawcutting Changes the ‘Energy in a Pavement”
It is like moving the ball in this dish

Stable Cracking is shown where movement results in the ball coming back



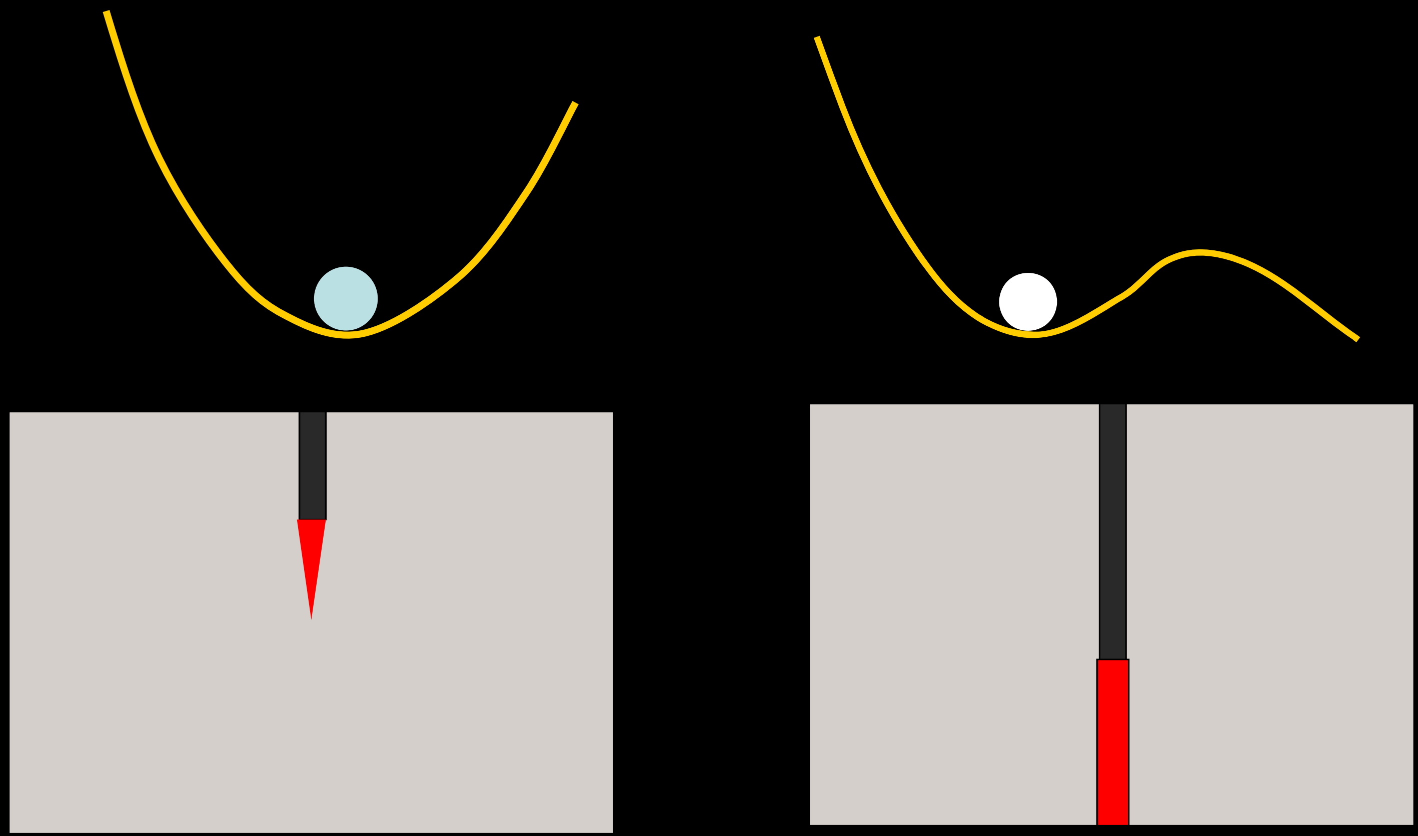
Stable vs. Unstable Cracking

Sawcutting Changes the ‘Energy in a Pavement”
It is like moving the ball in this dish

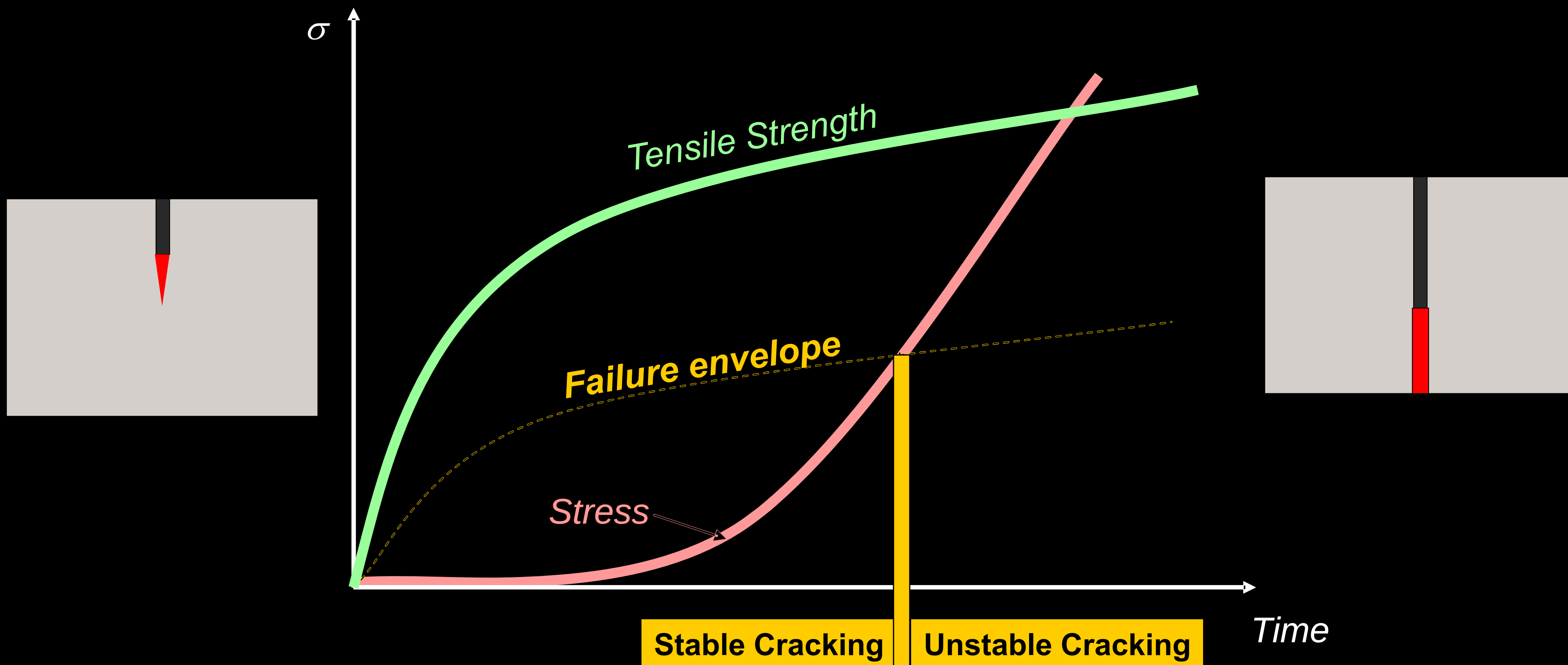


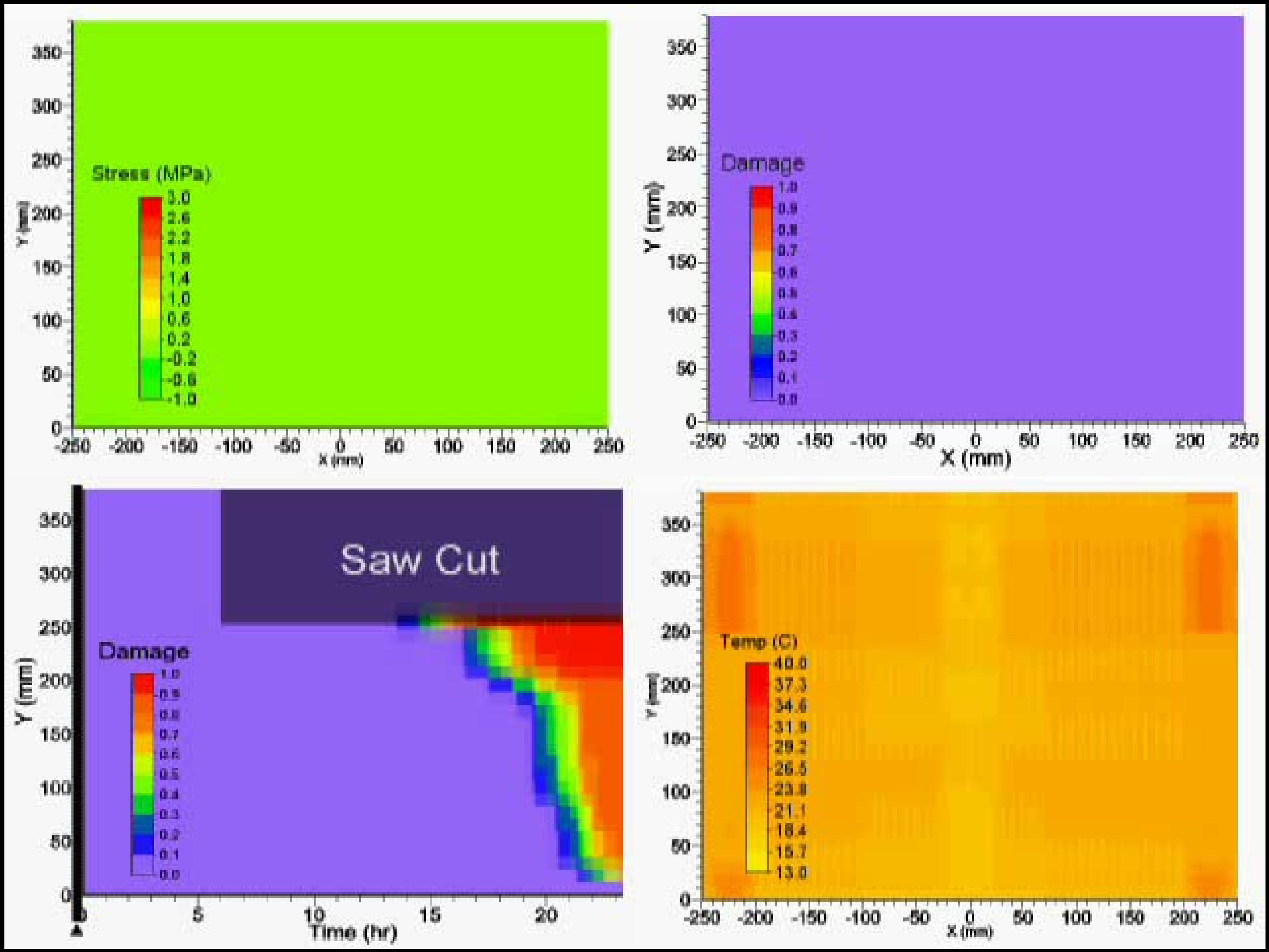
Unstable Cracking is shown where movement results in the ball is does not return to a stable spot

Stable vs. Unstable Cracking



Comparing Stress and Strength When a Cut Exists




Stress (MPa)
3.0
2.6
2.2
1.8
1.4
1.0
0.6
0.2
-0.2
-0.6
-1.0
Damage
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Y (mm)
X (mm)
Saw Cut
Time (hr)
Temp (C)
40.0
37.3
34.6
31.9
29.2
26.5
23.8
21.1
18.4
15.7
13.0

Conclusions

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College of Engineering

- Used a computer to simulate early age concrete
- Examined the influence of the environment and construction operations
- Case I – No Saw-Cutting
- Case II – Saw-Cutting
- Cutting at Later Ages is Less Stable
- Developed A Strength Reduction Factor
- If Late in Cutting, Cut Shallow then Make Larger