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MichiganTech

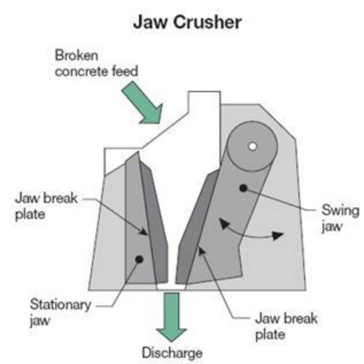
Characterization of Recycled Concrete Aggregates for Reuse in Rigid Pavements

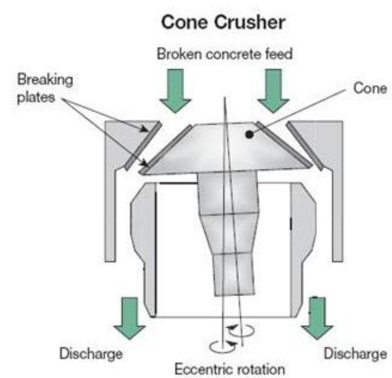
Acknowledgements

- Michigan Department of Transportation (MDOT)
- Minnesota Department of Transportation (Mn/DOT)
- MTU Tomasini Fund
- Students
  - Rita Lederle
  - Morgan Hansen
  - Cory Shorkey

Recycled Concrete Aggregates (RCA)

- RCA is old concrete that has been removed, crushed, and sized for reuse
- Old aggregates as well as old mortar and some unhydrated cement
- RCA can contain contaminants
- RCA differs depending on crushing process





Impetus for Study

- RCA use in concrete goes back to post WWII Europe
- MDOT was pioneer of RCA use in rigid pavements in the USA in 1980's
  - 1050 lane-km constructed
  - Moratorium for use in rigid pavements in 1991
- Costs from landfill, transportation, and quality aggregates has brought issue back into play
- Sustainability

I-94 West of Kalamazoo, Michigan, USA

- JPCP after 10 years
- Shrinkage cracking
- Wide joints and cracks
- Low load transfer

Some RCA Issues for Reuse in Concrete Surface Layer

- Varied crushing processes and high fines
- D-cracking and Material-related distress potential
  - High alkalinity of water runoff
- Leachates (calcium) and high pH for base material
- High absorption (mortar / unhydrated cement)
- Less volumetric stability
  - Shrinkage, creep, and carbonation

Laboratory Study

- Aggregate Characterization
  - Absorption capacity
  - Specific gravity

  } **Using three methods**
- Address RCA in comparison with virgin aggregate concrete
  - Hardened air content
  - Shrinkage (drying, autogenous, and restrained)

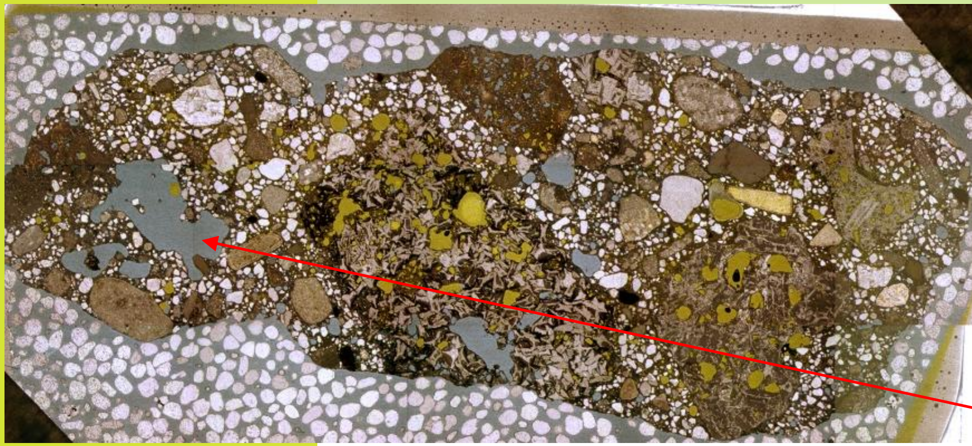
Coarse Aggregate Sources

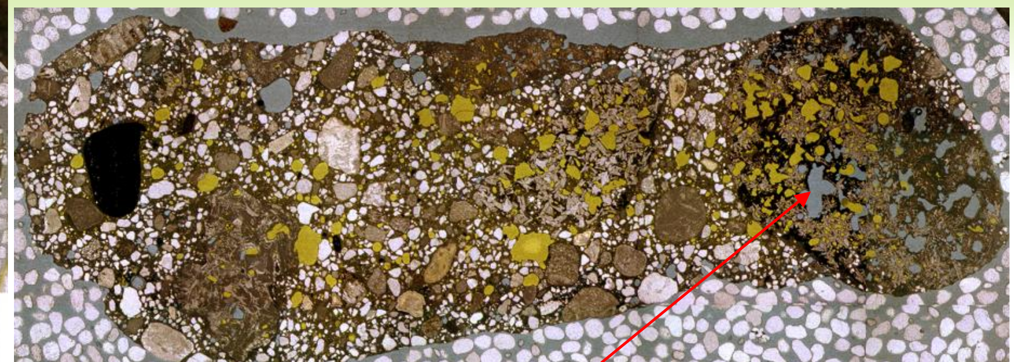
- Natural aggregates
  - Crushed gravel
- RCA (with original aggregate type)
  - RCA limestone
  - RCA blast furnace slag
  - RCA crushed gravel
  - Recycled RCA crushed gravel (3G/Twice recycled)
- Fine aggregate → natural sands

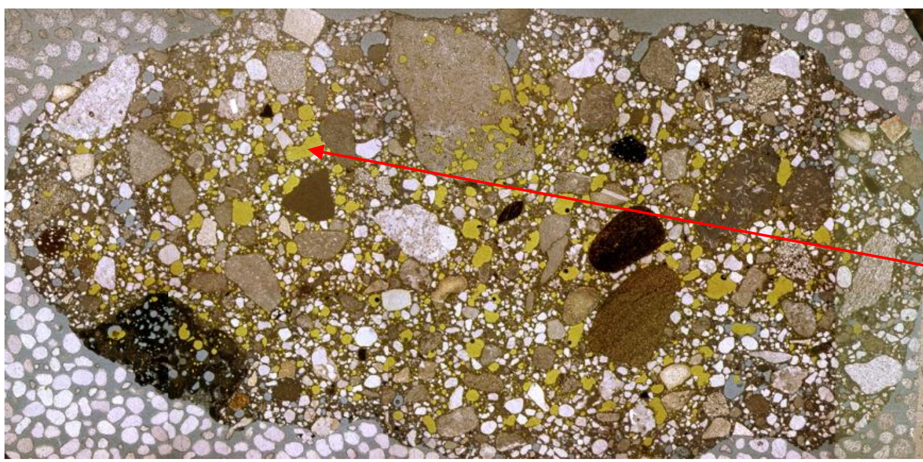
Differences in Absorption Capacity and Porosity

- Standard ASTM C127
  - 24-hour absorption
  - Visual assessment of SSD →High variability
- Helium Pycnometer and envelope density analyzer (EDA)
  - Automated
  - Assess water absorption?
- Image Analysis

Image Analysis - Aggregate Thin Sections







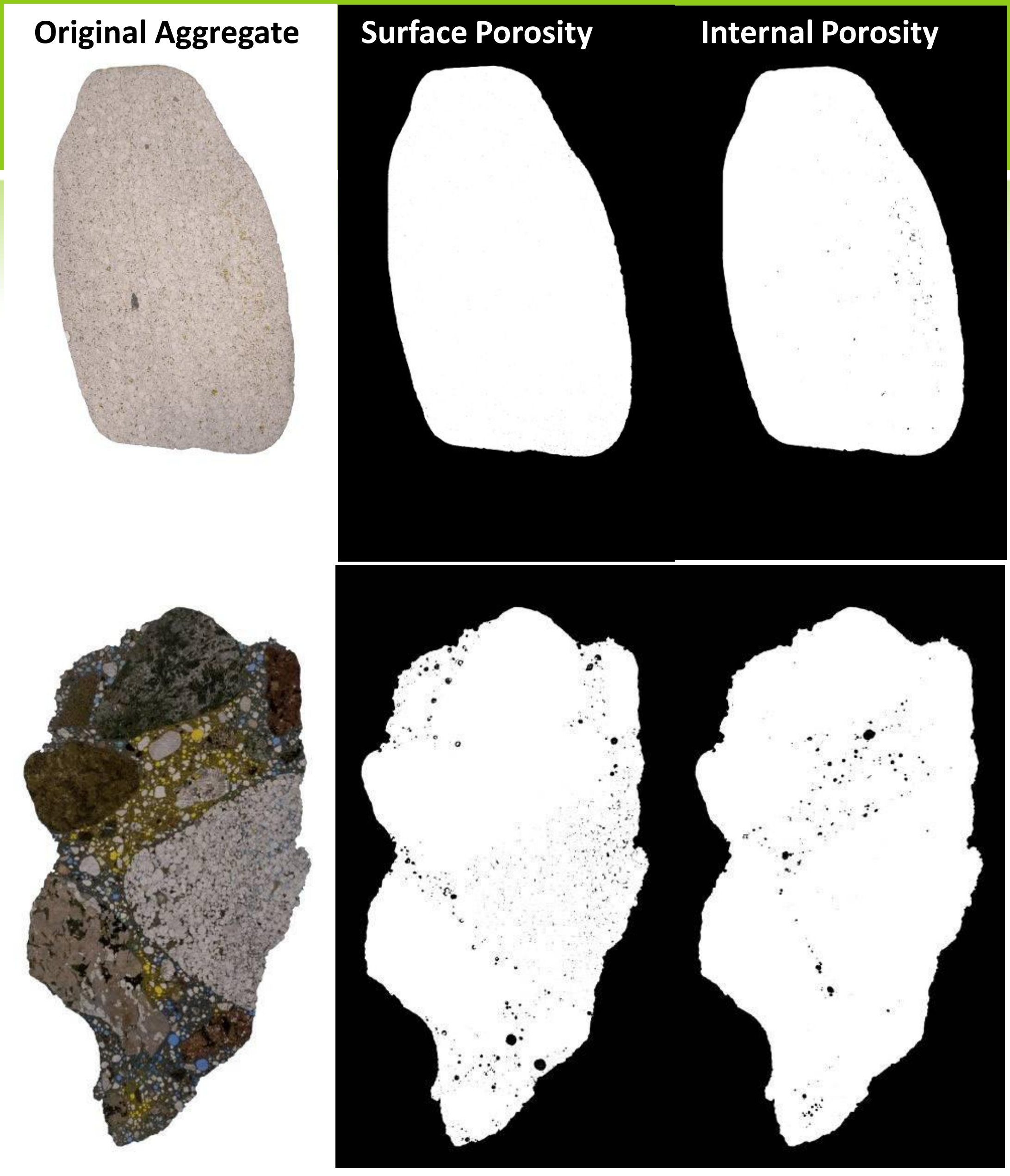
Surface porosity

Internal porosity

Using Impregnated resins with specified viscosities

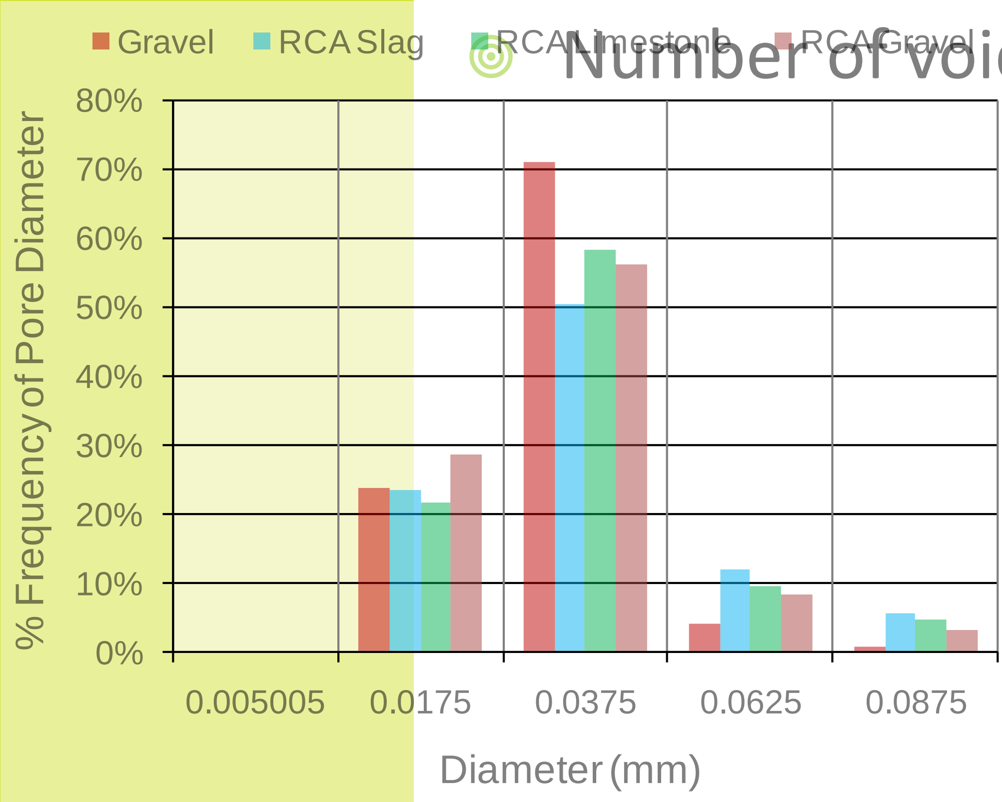
Image Analysis

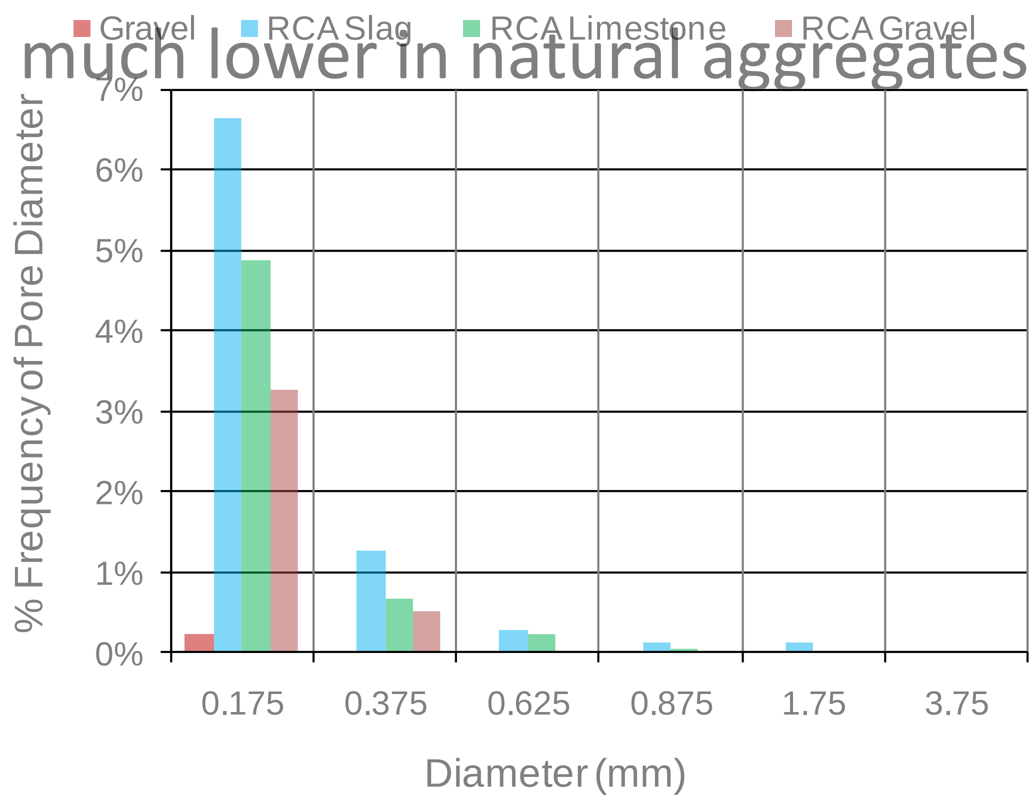
- Imaging software to assess
  - Pore sizes
  - Locations
  - Distribution
- Leads into future research in moisture diffusivity and poromechanics



Pore Size Distribution of Aggregates

- Natural aggregates void of larger Feret's diameter
- Number of voids much lower in natural aggregates





Surface Porosity by Multiple Methods

$$A = \frac{n}{G_B}$$

- Image Analysis matches He Pyc /EDA
- Does ASTM C127 capture porosity/AC for highly porous aggs?

RCA Concrete Mix Proportioning

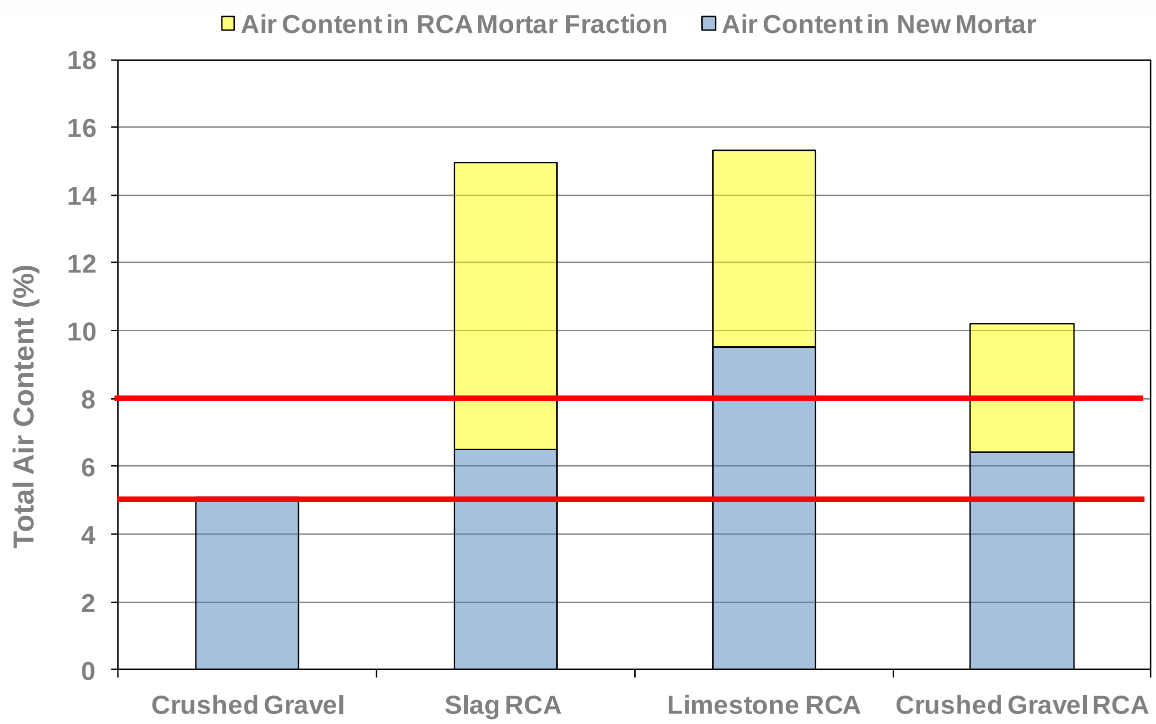
- 0.42 water-to-cement ratio
  - No SCMs
- 362 kg cement per m^3 of concrete
- 72% bulk volume of aggregate to vol. of concrete
  - Paving mixes high in coarse aggregate content
- Air entrained (target= 6.5%, range of 5.5 – 8.5%)
- Target slump 50mm
  - Monitor fresh properties over time

Fresh Properties

- Measured slumps consistently higher than expected for RCA concretes
  - Met specs for natural aggregate concretes
- Slump loss was more dramatic in RCA concrete
  - Shorter window of workability
  - Harsh mixes with poorer consolidation
  - Superplasticizers helped to some degree
- Fresh air content specification difficult to meet

Hardened Air Content

- RCA occupies same bulk volume
- Contains more void space
- Moisture / chloride movement



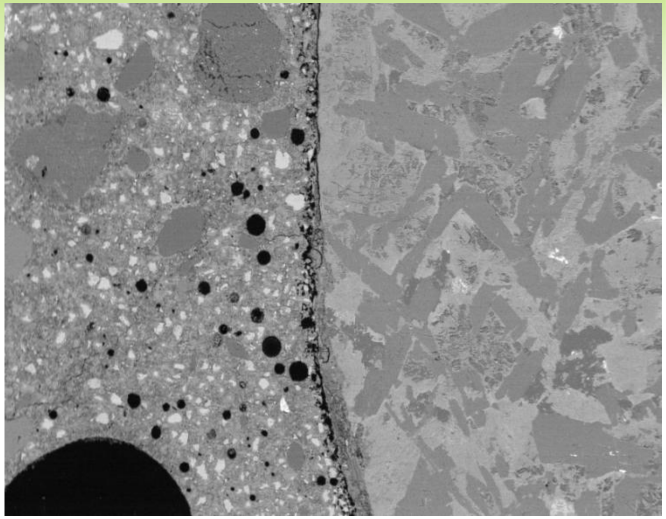
Air Void System Quality

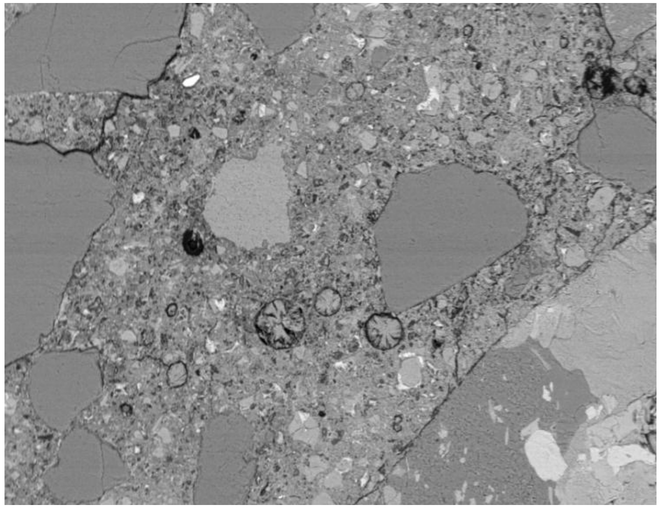
- RCA concretes showed better air void system connectivity in general
- Dependent on old concrete's quality
- Counterintuitive

Aggregate	Void Frequency	Within Criteria	Specific Surface Area (mm^{-1})	Within Criteria	Spacing Factor (mm)	Within Criteria
Crushed Gravel	0.187	N	16.3	N	0.303	N
Slag RCA	0.339	Y	18.4	N	0.237	N
Limestone RCA	0.522	Y	23.8	N	0.140	Y
Crushed Gravel RCA	0.509	Y	29.8	Y	0.153	Y

Optical and Scanning Electron Microscopy

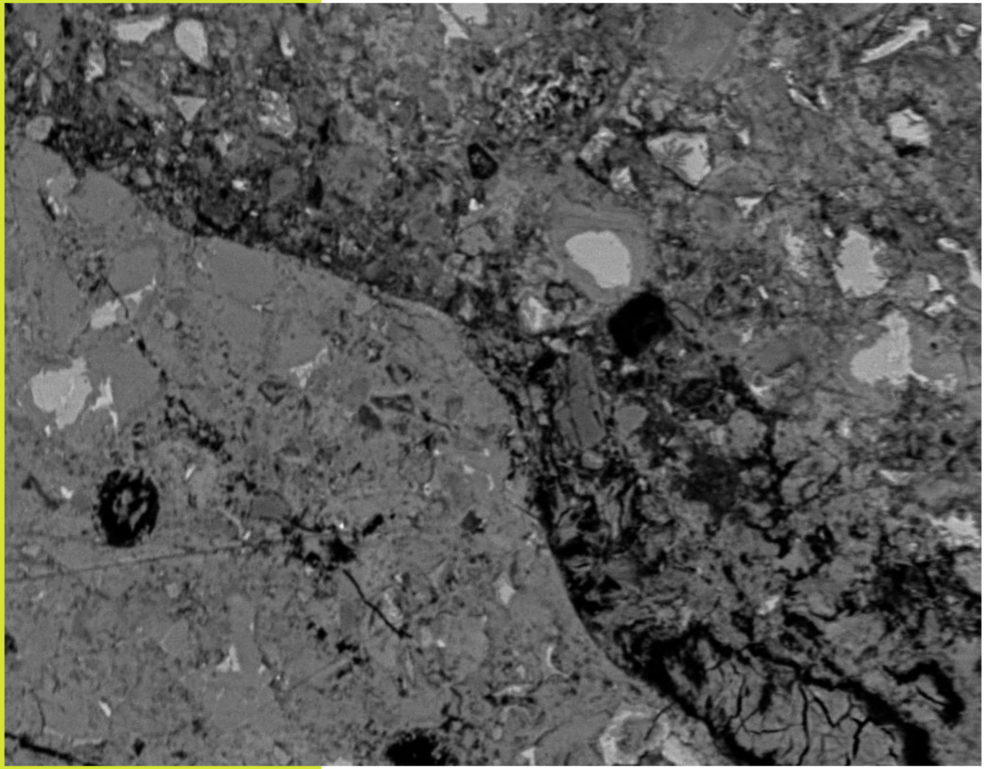
- Porous interfacial transition zones (ITZ)
- Ettringite filled pores of 3G concrete samples
  - Good performance of 3G concrete
- Microcracking in old mortar from crushing process
  - Reduced fracture resistance

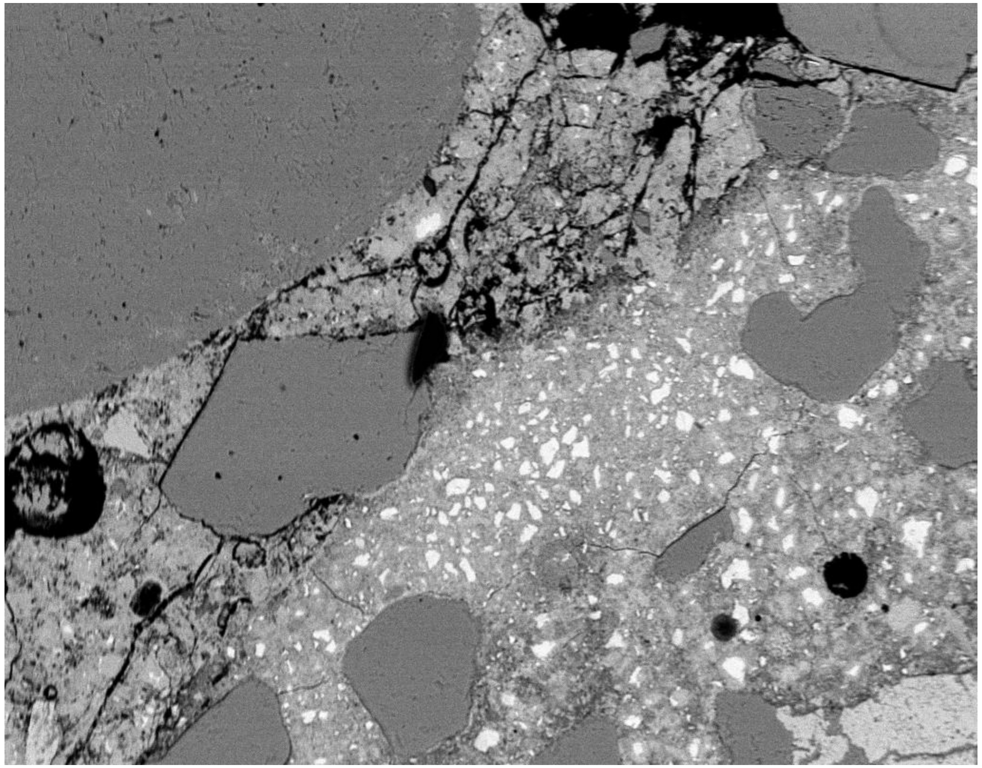




Distinct Mortar Phases

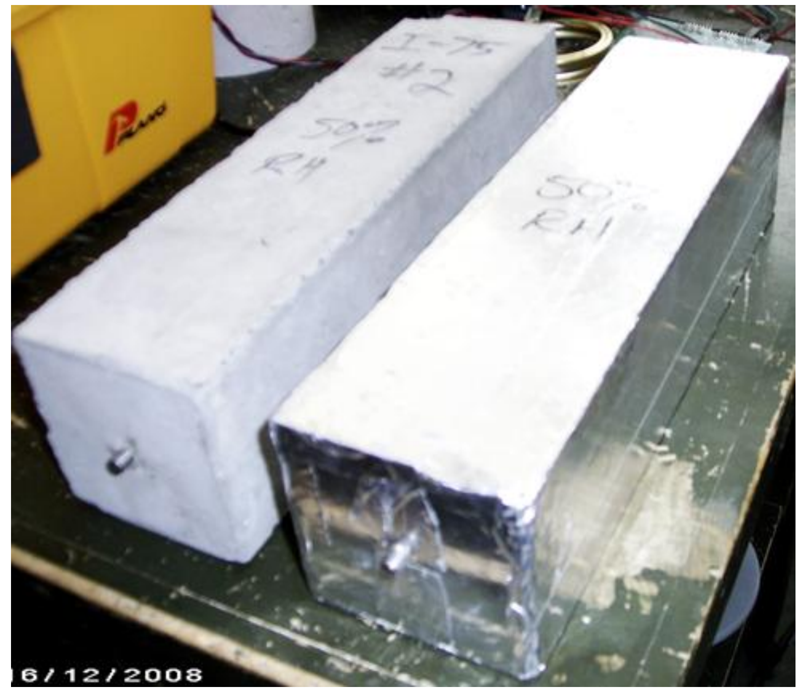
- Some evidence of multiple ITZs





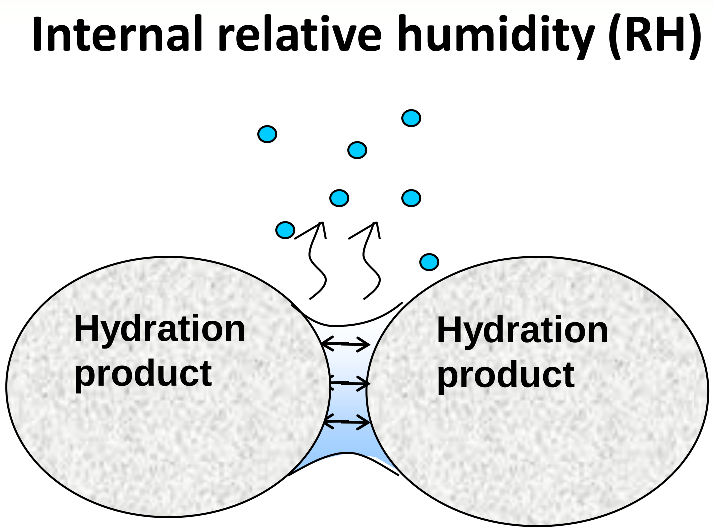
Shrinkage Specimens

- 1-D shrinkage
  - ASTM C 157
  - Sealed (autogenous)
  - Unsealed
  - Difference is drying shrinkage
- Stored at constant relative humidity, then switched after 1 year, then every 30-45 days



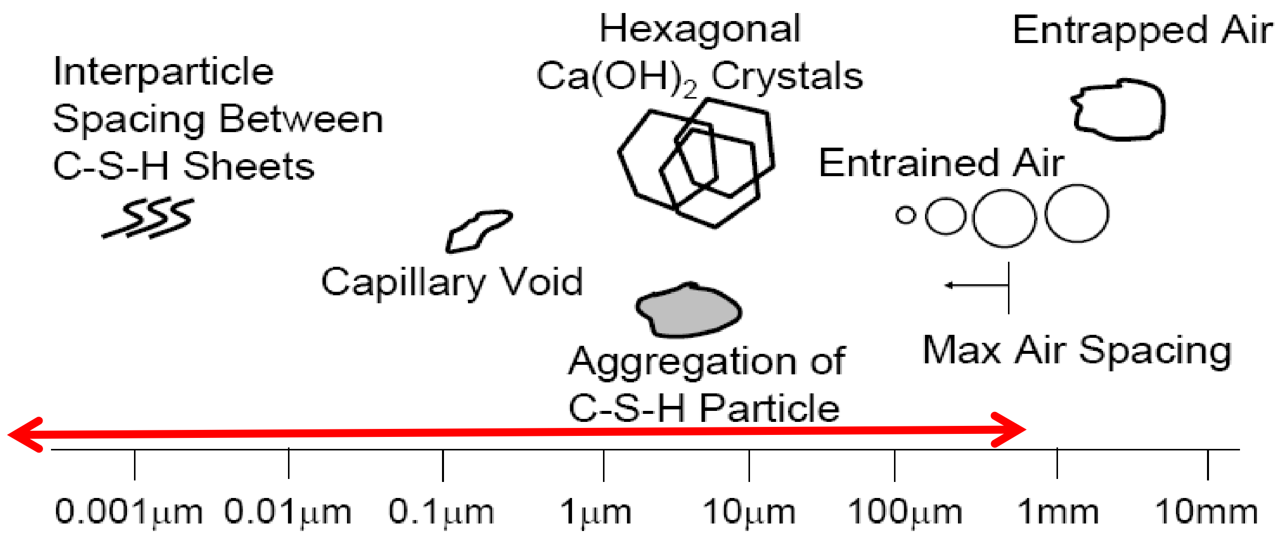
Mechanism of shrinkage

- Shrinkage in concrete is dominated by capillary surface tension mechanisms
- As water leaves pore system, curved menisci develop, creating reduction in RH and "vacuum" within the pore fluid



Voids in Concrete

- RCA concrete contains higher percentage of entrained air through gel pores
  - Affects concrete durability and structural properties

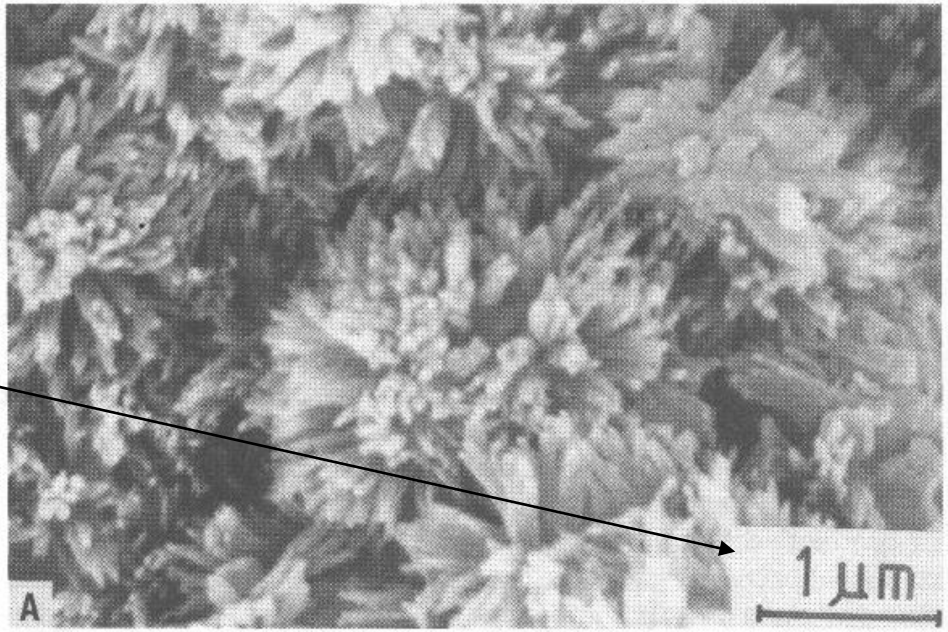


VISUALIZING THE SCALE OF SHRINKAGE MECHANISMS

- Capillary stresses present in pores with radii between 2-50 nm

Scanning electron micrograph from Taylor "Cement Chemistry" (originally taken by S. Diamond 1976)

Note the dimensions



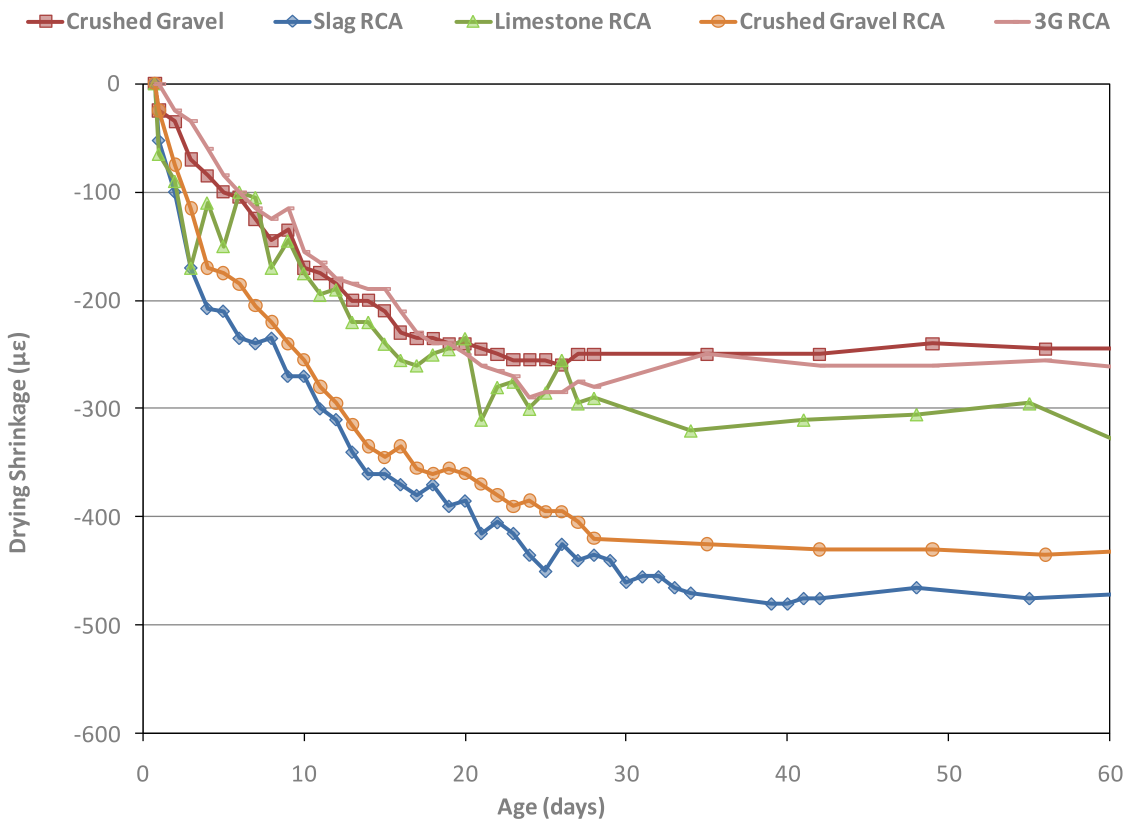
- C-S-H makes up ~70% of hydration product
  - Majority of capillary stresses present in C-S-H network

Drying Shrinkage in RCA Concrete

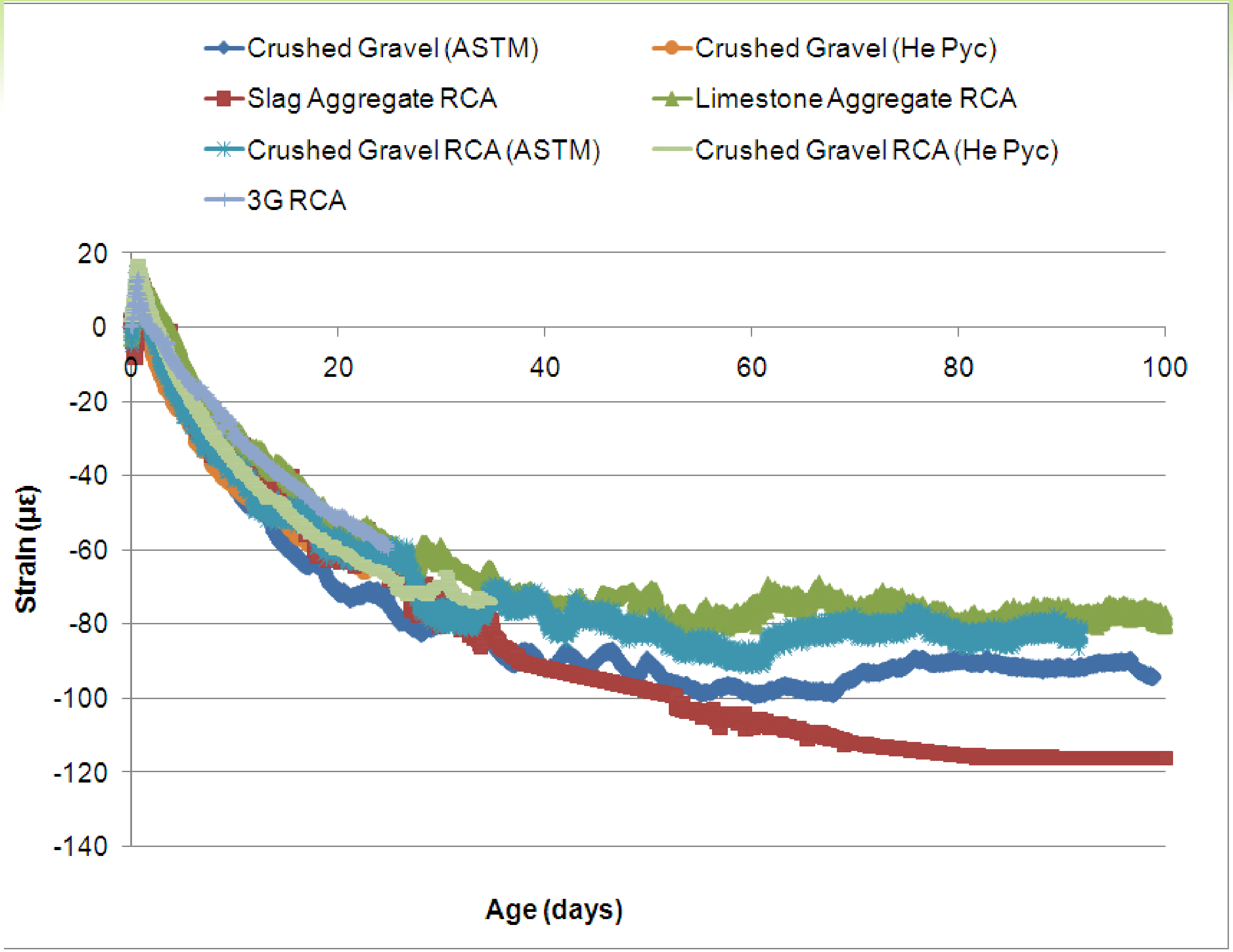
- Thought to be a driving force in deterioration of JPCPs in many cases
  - Higher amount of capillary pores from attached mortar
  - Unhydrated cement particles
- Previous pavement design methods have not taken this into account
- Pavement mechanics are now being utilized to capture effects

Drying Shrinkage at 50% RH

- Significantly higher for RCA concrete
- Capillary porosity exists in RCA and new mortar
  - Crushing



Restrained Shrinkage Strains



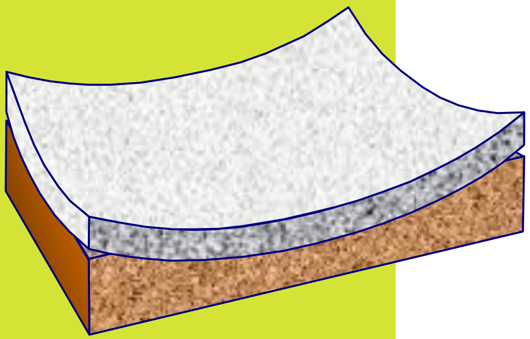
RCA Concrete Slabs under Restraint

- While drying shrinkage is higher in RCA concretes …
  - Increased creep characteristics of RCA concrete can relax strains at early ages
  - At later ages, creep is less effective in controlling strain magnitudes and deflections
- Rigid pavement is restrained from dowels, tie bars, slab-base friction/bonding, and self-weight

Moisture in Concrete Pavement Slabs

- Due to this semi-porous nature of concrete
  - Moisture can get in and out of pores
  - Due to simplicity of pavement geometry, typically through surface
- Below depth of 50-100mm in concrete slab
  - Moisture content is nearly saturated and consistent
- Top 50-100mm varies with rain events, ambient relative humidity, wind, etc.
  - Leads to highly non-linear moisture gradients in slab

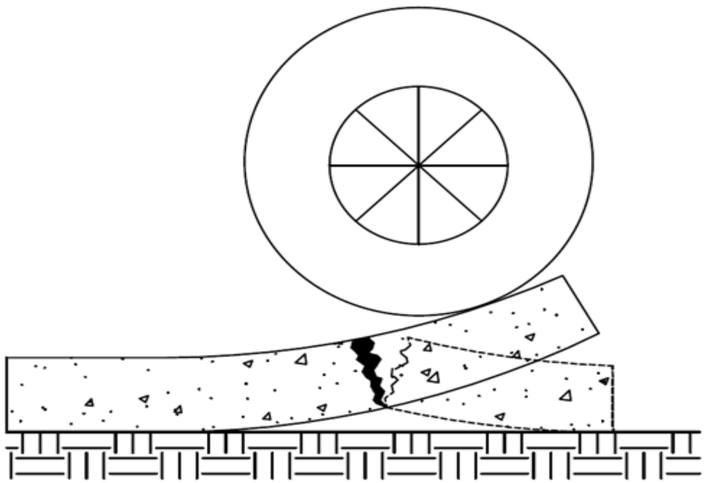
Moisture Loss Effects



- Occurs through both self-desiccation and drying
  - Both cause volumetric changes
  - Autogenous (self-desiccation) happens throughout concrete
  - Drying shrinkage is a gradient within concrete
- Drying shrinkage and warping are linked
  - Tied to gel pores and smaller capillary pores
  - Differential drying shrinkage – permanent
  - Warping – reversible portion of shrinkage

Why Curl and Warp Matter

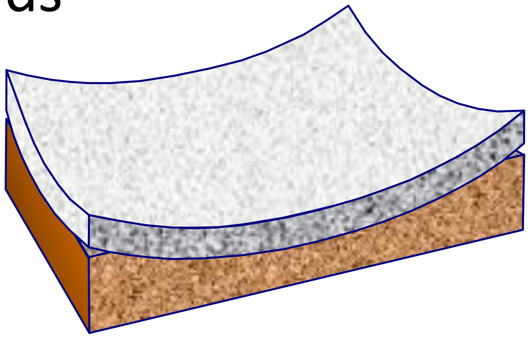
- Stresses induced by environmental loading can be enough to crack a slab
- Slab corners can be unsupported
- Changing boundary conditions
- Change in primary failure mechanism
- Premature fatigue failure



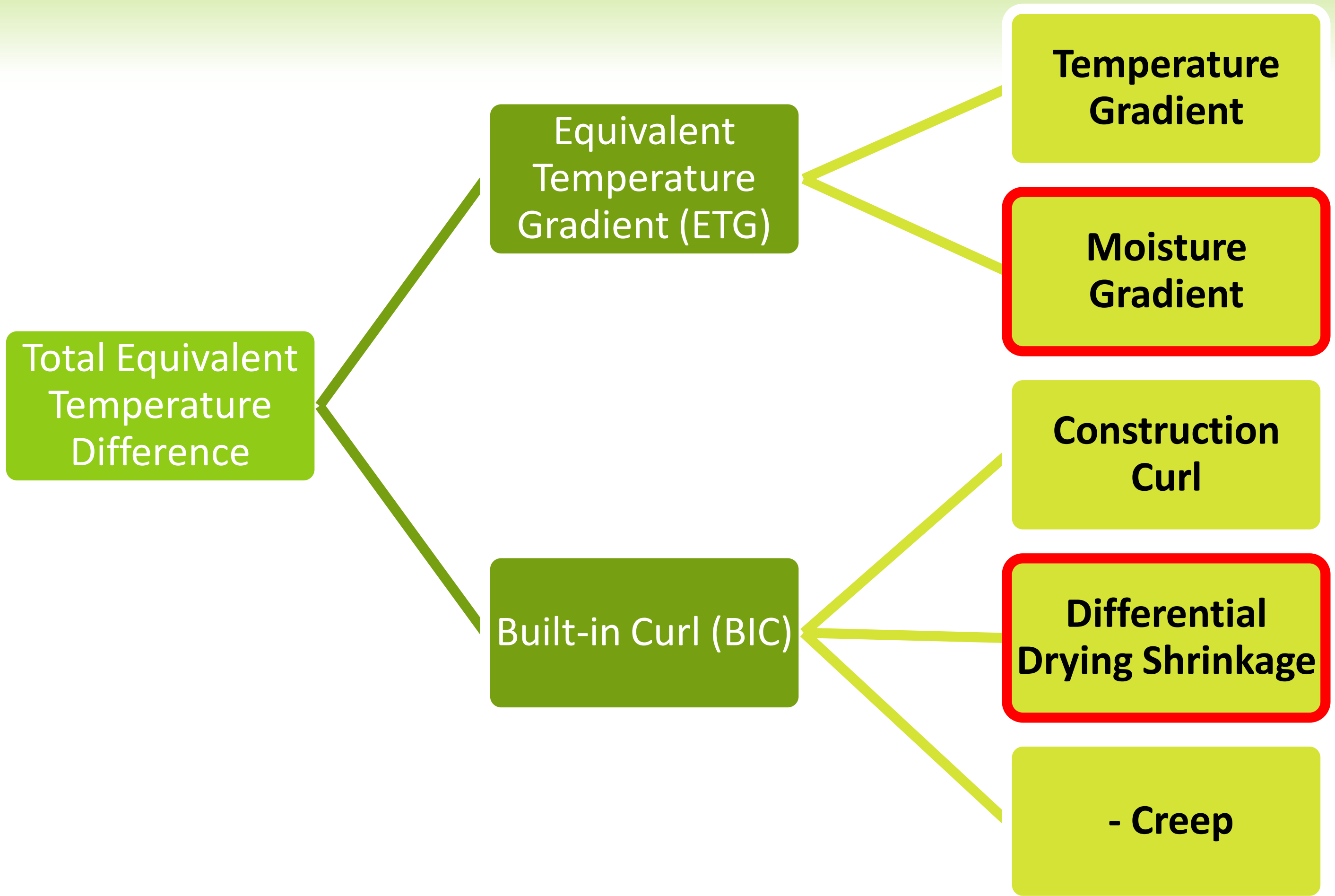
Top-down cracking from combined environmental and traffic loading

Drying Shrinkage leading to Slab Deformation

- Warping and built-in curling issues can lead to alternative fatigue cracking development
- Gaps under slab corners
  - Interaction with external loads

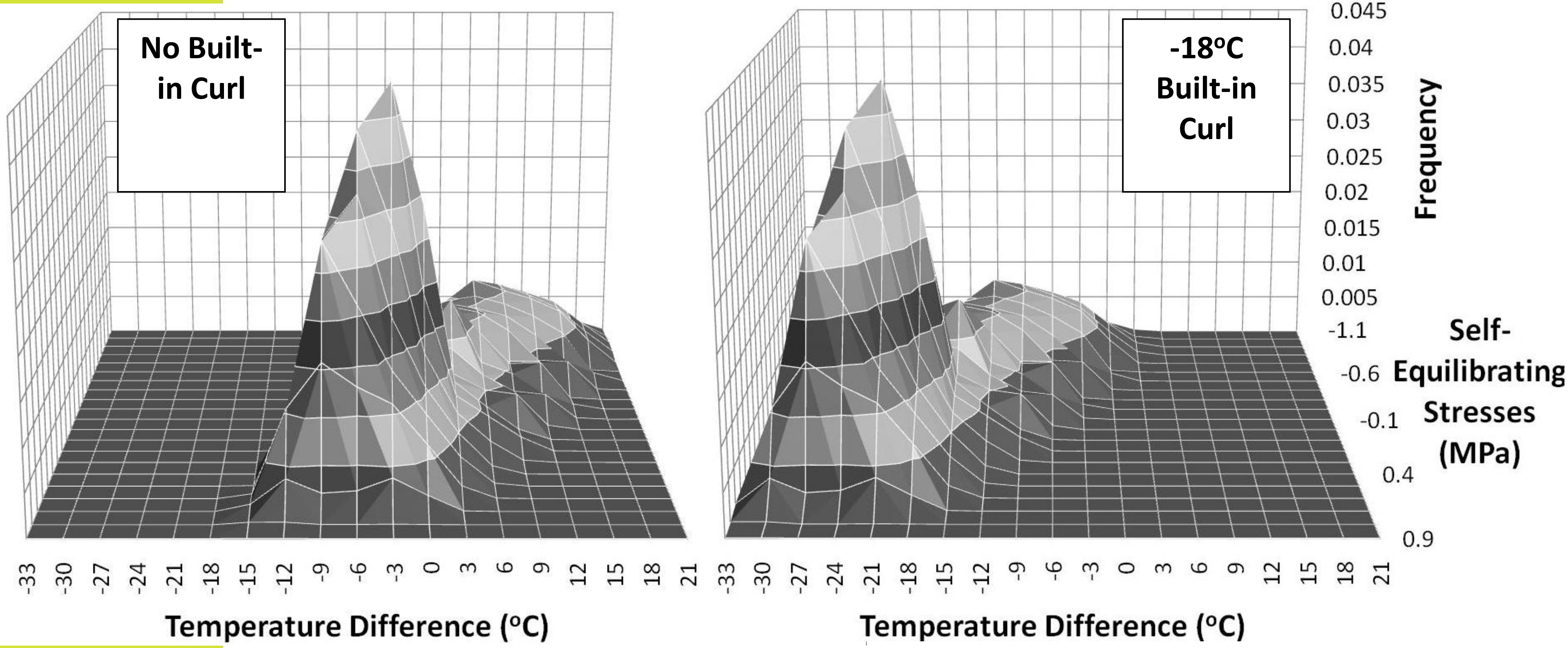


Volume Change Components in the Mechanistic-Empirical Pavement Design Guide (MEPDG)



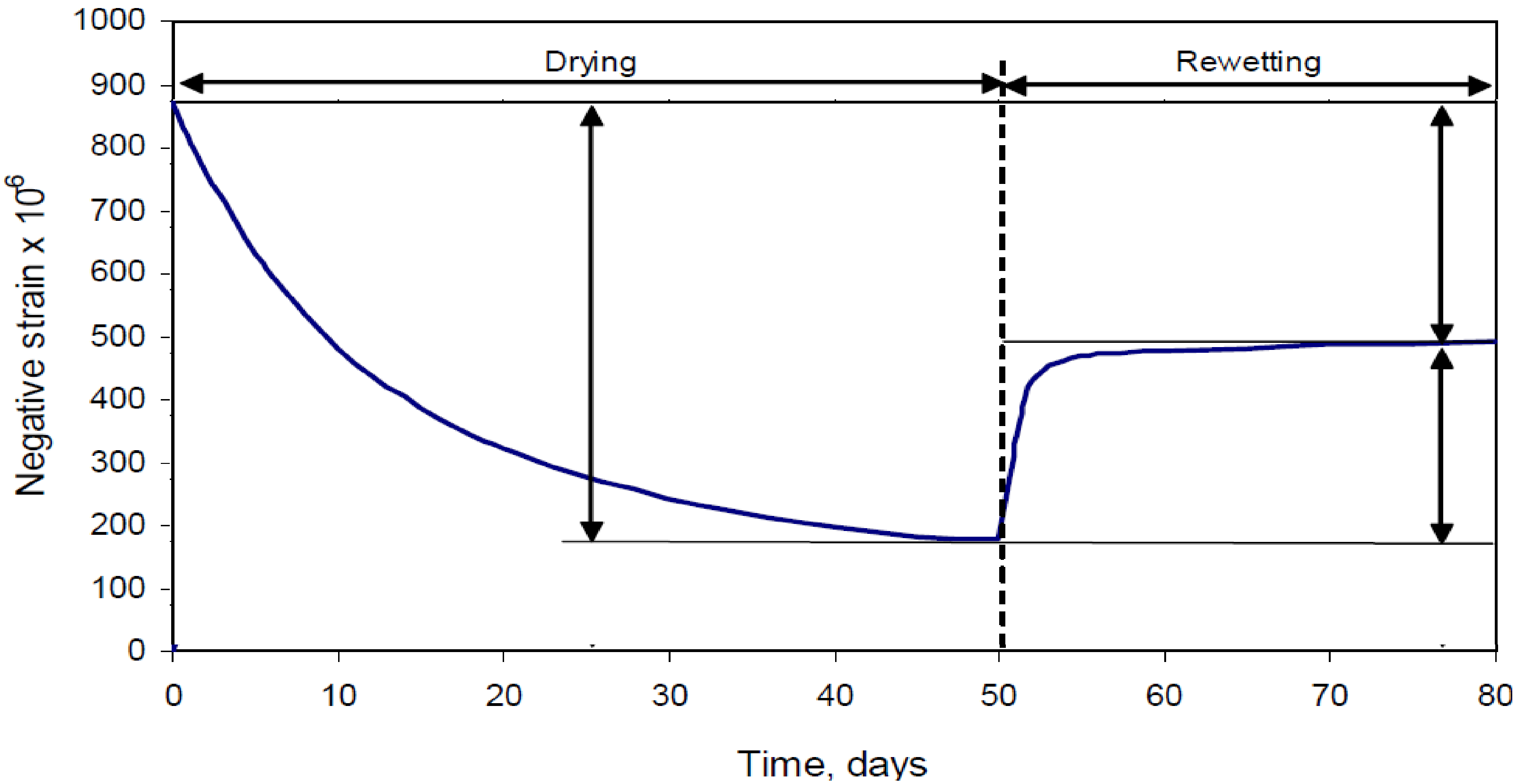
Temperature Shift Due to Built-in Curl

- Shift can be large enough to never "curl down"



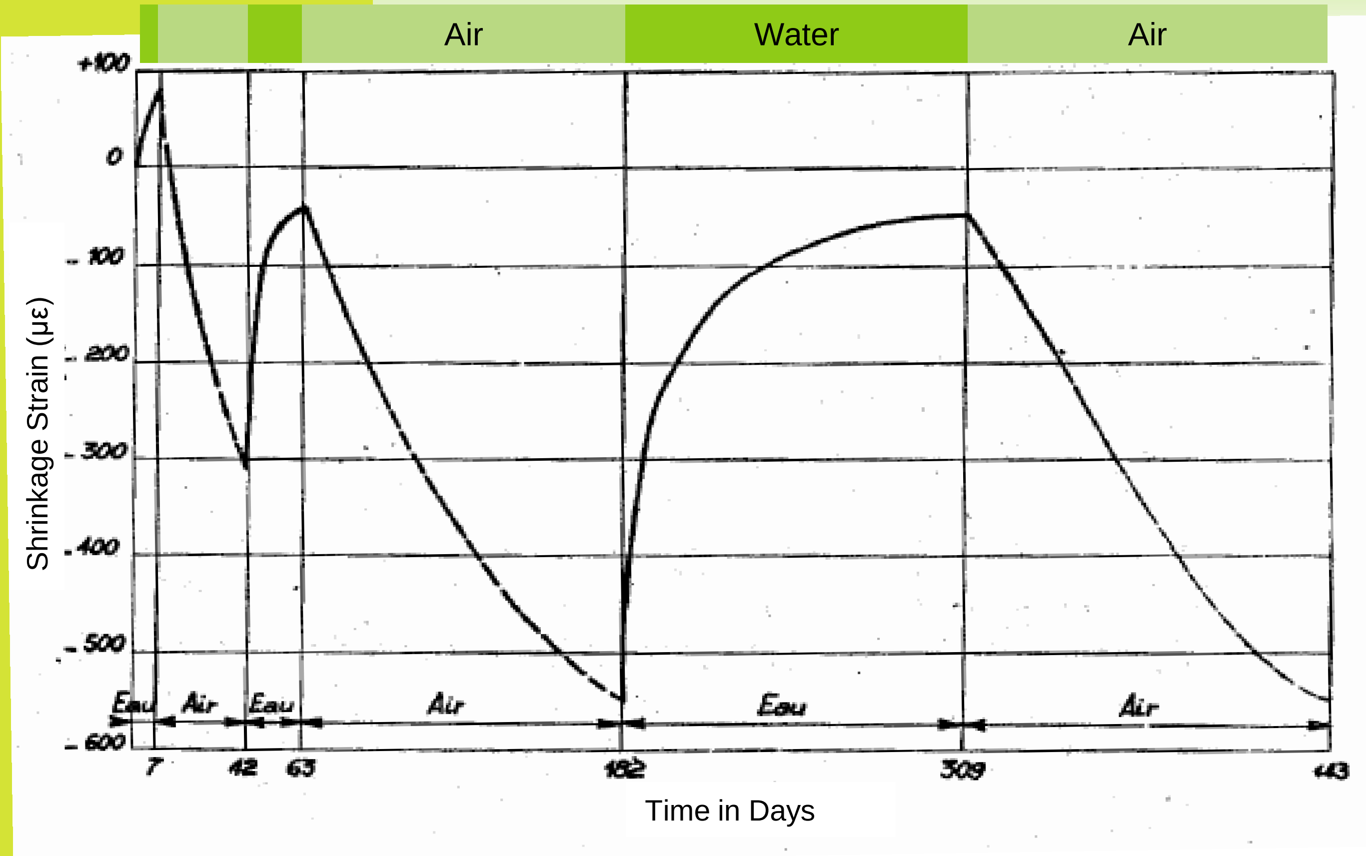
Reversible Shrinkage - Introduction

- Portion of shrinkage is reversible
- Assumed to be 50% in MEPDG



Mindness and Young, (1981.) *Concrete*. Prentice Hall, Englewood Cliffs, NJ.

Reversible Shrinkage – Past Research



L'Hermite, R.L. (1947) "Le Retrait Des Ciments, Mortiets et Betons." Laboratioires du Batiment et des Travaux Publics.

- Some research in Europe from 1940-1975
- 40-70% of shrinkage is reversible
- Mortars stored in water for an extended cure had complete shrinkage reversibility

Mechanism of Reversible Shrinkage

Neville, A.M., *Properties of Concrete*. 4th ed. 1997, New York: Wiley & Sons, Inc.

- The mechanism is not well understood
- Neville hypothesized that C-S-H gels form bonds when they are in close proximity during drying phase
- When the concrete is again exposed to moisture, these bonds swell, but hold the matrix together
  - Preventing shrinkage from being fully reversible

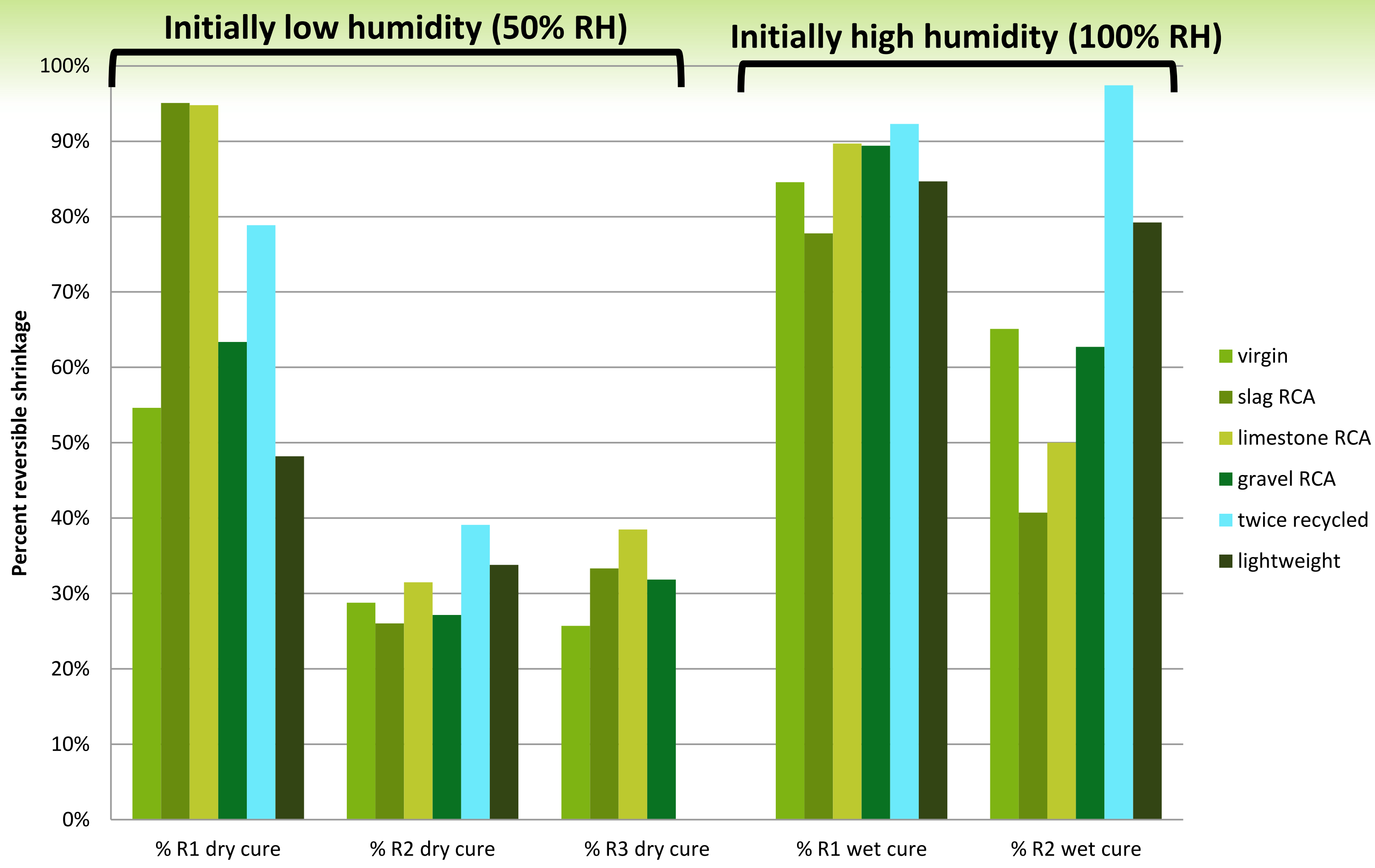
Mechanism of Reversible Shrinkage

Granger L., Torrenti J.M., and Acker P., Thoughts About Drying Shrinkage: Scale Effect and Modelling. Materials and Structures, 1997. 30(3): pp. 96-105.

Sellier A., and Buffo-Lacarrière L., "Vers une Modélisation Simple et Unifiée du Fluage Propre, du Retrait et du Fluage en Dessiccation du Béton. Revue Européenne de Génie Civil, 2009. 13(10).

- Others hypothesize that a portion of irreversible shrinkage is related to microcracking
- During the shrinkage phase, microcracks are formed and open
- During swelling, cracks close either partially or fully
- Because these cracks cannot be reversed, some portion of drying shrinkage is believed to be irreversible

% Reversible by Agg Type



Warping & DDS - Final Models

Lederle, R.E., and Hiller, J.E., Development of New Warping and Differential Drying Shrinkage Models for Jointed Plain Concrete Pavements Derived with a Nonlinear Shrinkage Distribution, Accepted to the Transportation Research Record, 2012.

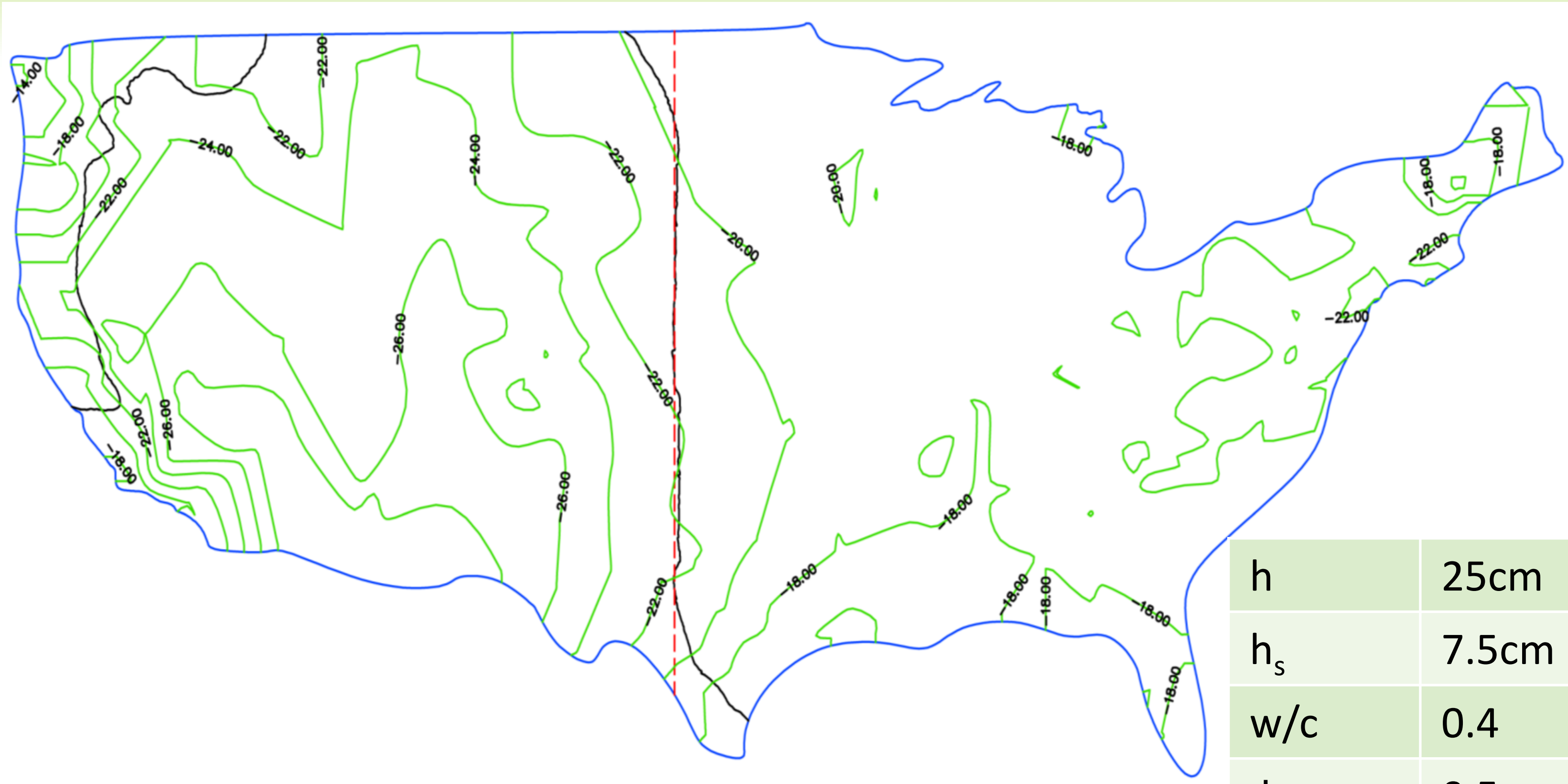
- Non-linear model for equivalent temp. difference due to drying shrinkage in concrete pavements
- Warping model

$$ETG_{warp} = \frac{\phi \text{Я} \omega \varepsilon_u h_s [-3h(-4+\pi) - 20h_s + 6\pi h_s](1-\mu)}{2h^2 \alpha}$$

- Differential Drying Shrinkage model

$$ETG_{DDS} = \frac{(1-\phi) \text{Я} \omega \varepsilon_u h_s [-3h(-4+\pi) - 20h_s + 6\pi h_s](1-\mu)}{2h^2 \alpha}$$

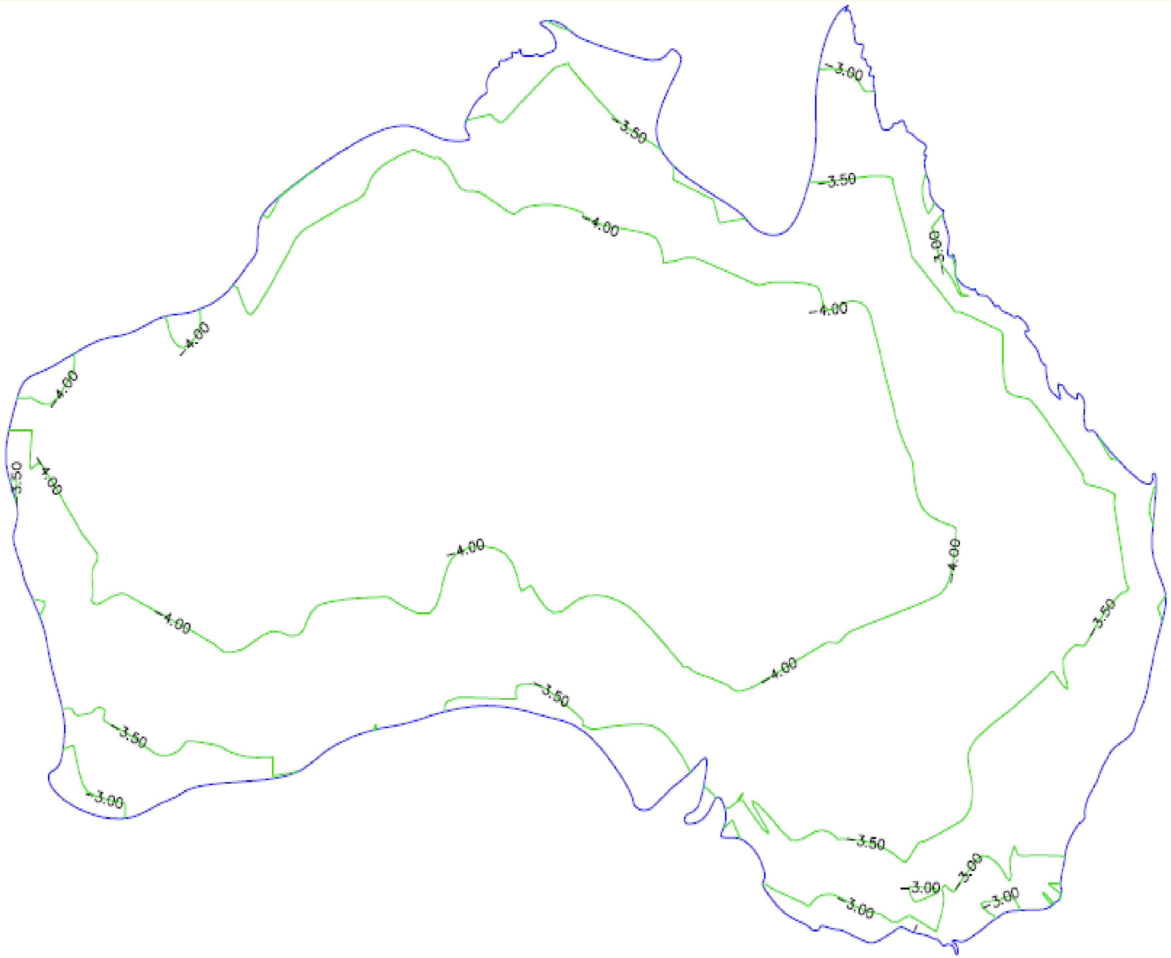
Warping & DDS – Design Aids



h	25cm
h_s	7.5cm
w/c	0.4
φ	0.5
ε_{su}	1200με

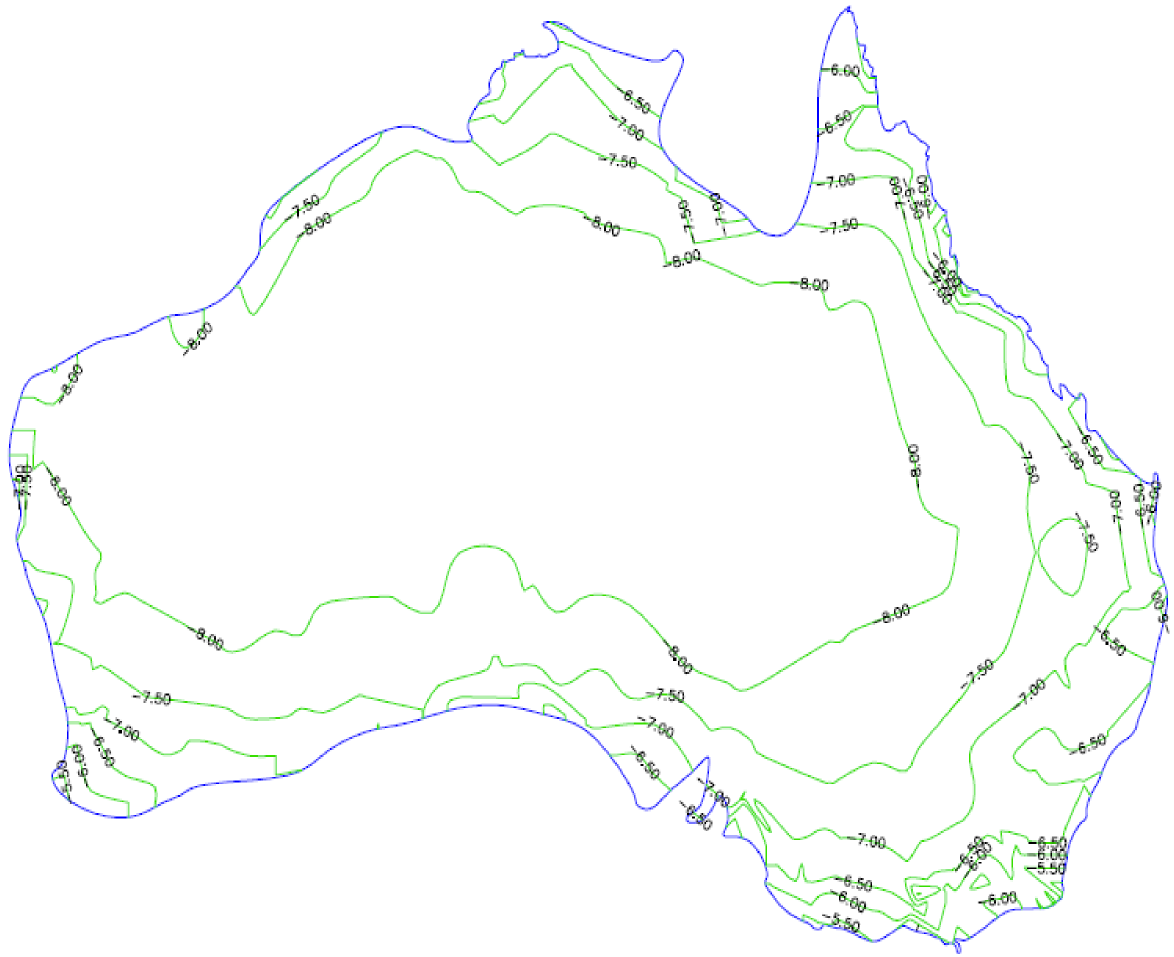
How This Affects Concrete Pavements in Australia

- Non-linear model for equivalent temp. difference due to drying shrinkage



How This Affects Concrete Pavements in Australia

- For RCA concretes
- Higher drying shrinkage
- More change in coastal regions



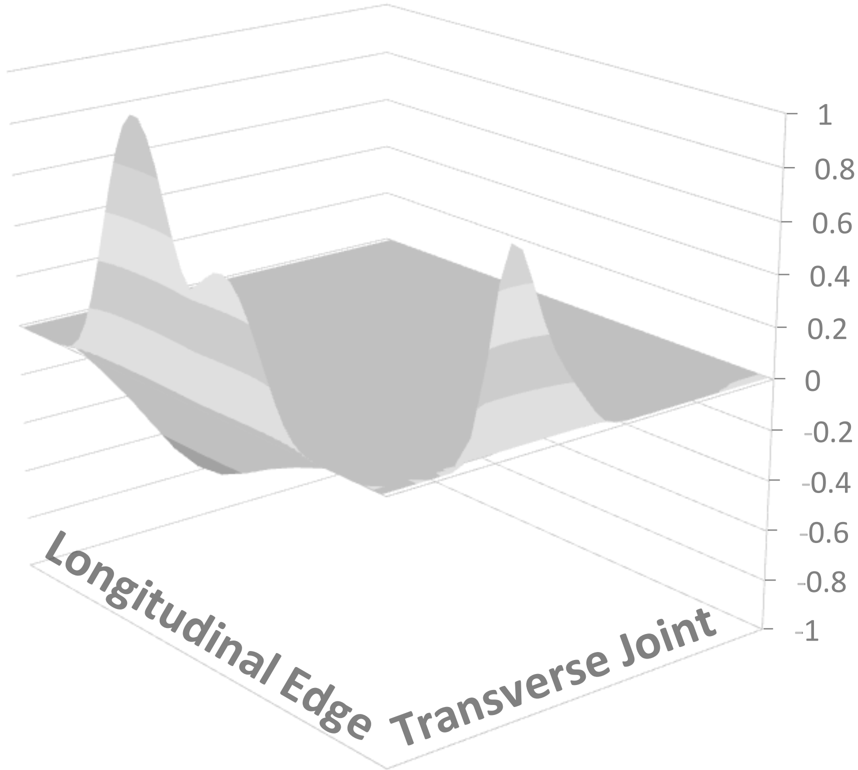
Significance of High levels of Permanent Differential Drying Shrinkage?

- Poor curing → High irreversible drying shrinkage
  - Leads to high levels of built-in curling in JPCP
  - Essentially causes equivalent temperature shift for specific climatic location
- MEPDG captures this effect to some degree
  - Only predicts transverse fatigue cracking
- To account for fatigue as transverse, longitudinal, or corner cracking →

RadiCAL
Rigid Pavement Analysis for Design in California

RadiCAL

- Mechanistic rigid pavement analysis tool
- Predict fatigue cracking at multiple locations
  - Transverse, longitudinal, corner cracking
  - Top-down or bottom-up
- Site-specific conditions, traffic, materials

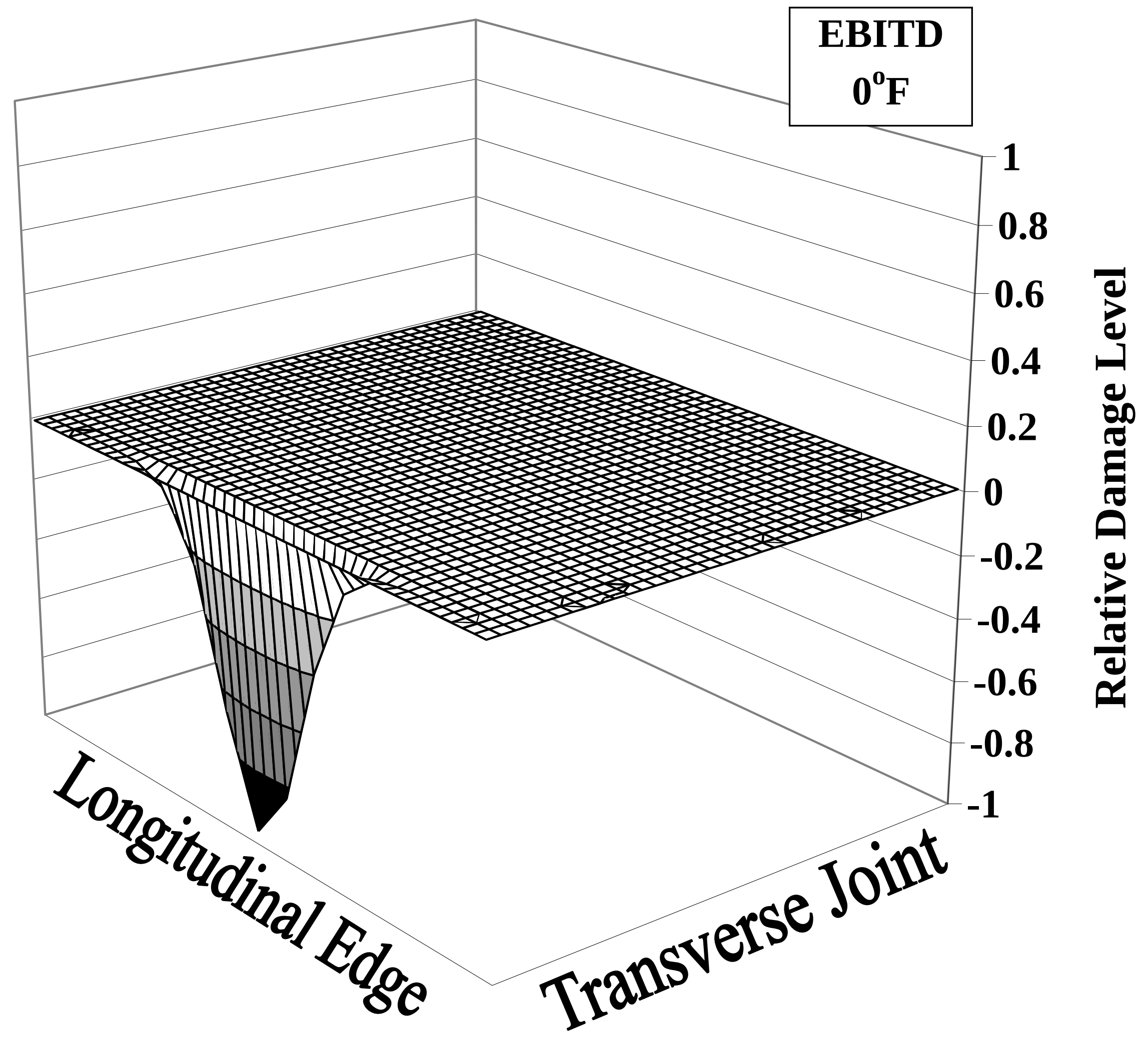


Low Load Transfer and 4.6m Joint Spacing

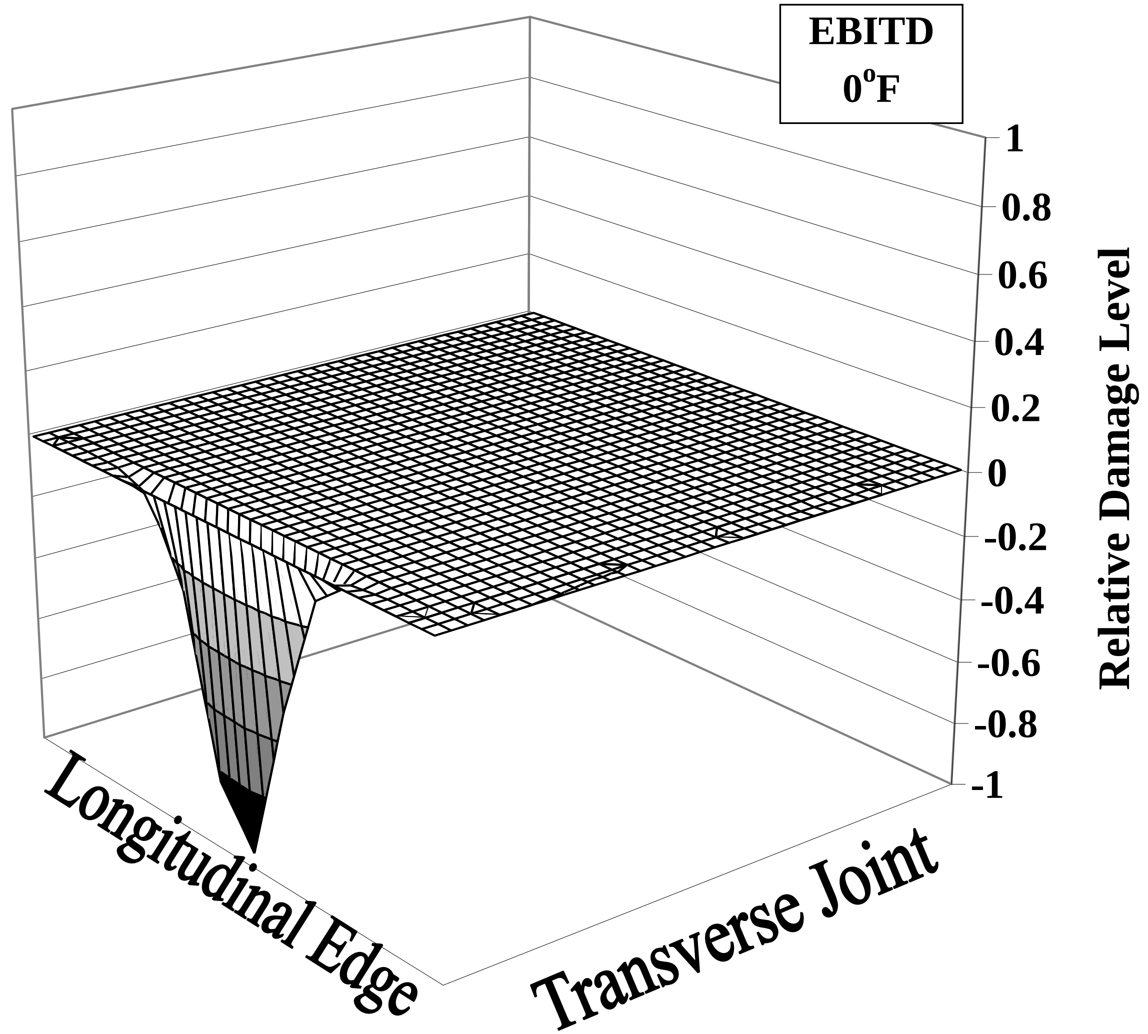
EBITD = Equivalent Built-in Temperature Difference

For temperature differences, °C = 5/9 °F

For San Francisco climate, traffic, soils, etc.



Low Load Transfer and 3.7m Joint Spacing



RCA Conclusions

- More unpredictable fresh and hardened properties using RCA in concrete
  - Need to account for existing air content in RCA
- RCA concrete shows higher drying shrinkage, but better creep characteristics
  - Account for some factors in mechanistic design methods
  - Creep may be advantageous in restrained pavements
- Must understand differences and plan for multi-generational use → Promote Sustainable Practices

RCA in Pvts Conclusions

- Past pavement design/analysis has not taken moisture warping into consideration directly
  - Not site-specific design
  - MEPDG attempts to account for this … unsuccessfully
- Amount of reversible warping can be controlled
  - Macro-level → curing conditions, w/c ratio, SCMs
  - Affects nano/micro-level → C-S-H gel spacing, micro-cracking
  - RCA concretes show no difference with virgin agg concretes
- Now have ability to capture these effects in pavement design, analysis, and construction practices

RCA Opportunities in Rigid Pavements

- Cost savings for right projects
  - Typically urban with crushing on-site
  - Michigan environmental policy to use RCA if up to 10% greater cost than virgin aggregates
- Knowledge and control of original project aggs
- Lower cement content can yield good performance
- Design adjustments to accommodate differences
  - Joint spacing, thickness, limited restraint, materials?
  - Two-lift construction?

Thank you …
Any questions?