Advanced Testing Methods

- Early-age shrinkage and resistance to cracking
- Thermal control
- Air-void analysis of fresh concrete
- Concrete rheology

Rheology of Fresh Concrete

- Terminology
- Bingham model for flow
- ICAR Rheometer
- Thixotropic behavior
- Optimization of concrete

Acknowledgement: Dr. Eric Koehler

Fresh Concrete

- fresh concrete—concrete which possesses enough of its original workability so that it can be placed and consolidated by the intended methods (ASTM C125)
  - Needs to be able to fill formwork without large voids
  - Needs to be cohesive so that segregation is not a problem
  - After filling formwork, needs to stiffen to reduce formwork pressure

Workability

- workability, n—that property of freshly mixed concrete that affects the ease with which it can be mixed, placed, consolidated, and struck off.(ASTM C125).
  - The slump test (ASTM C143/C143M) is the common method to indicate the workability of fresh concrete

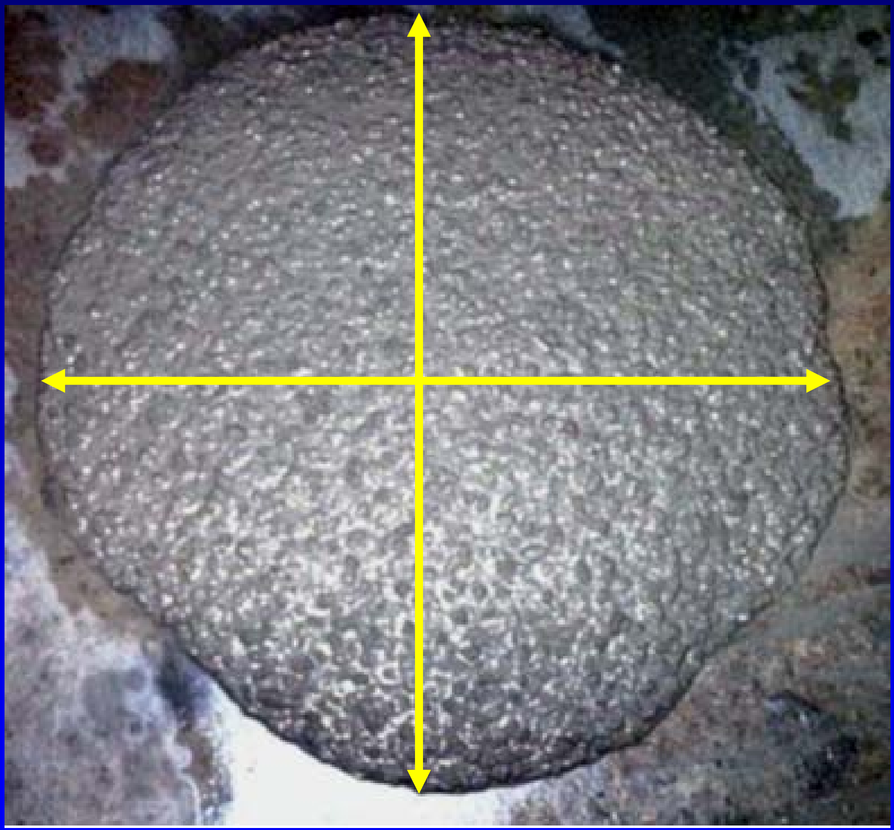
Consistency

- **consistency**, *n—of fresh concrete, mortar, or grout,* the relative mobility or ability to flow. (ASTM C125)

  DISCUSSION—This characteristic of fresh cementitious mixtures is difficult to quantify and empirical test methods have been adopted to provide indicators of consistency. For example, the slump test described in Test Method C143/C143M is used for concrete, the flow table method described in Test Method C109/C109M is used for mortar, and the flow cone method described in Test Method C939 is used for grout.

Slump Flow

- For self-consolidating concrete, the spread of the concrete in a slump test is used as an indicator of the flow behavior (ASTM C1611/C1611M)



Question

- Does the slump test (or slump flow test) provide enough information about the flow behavior of fresh concrete?

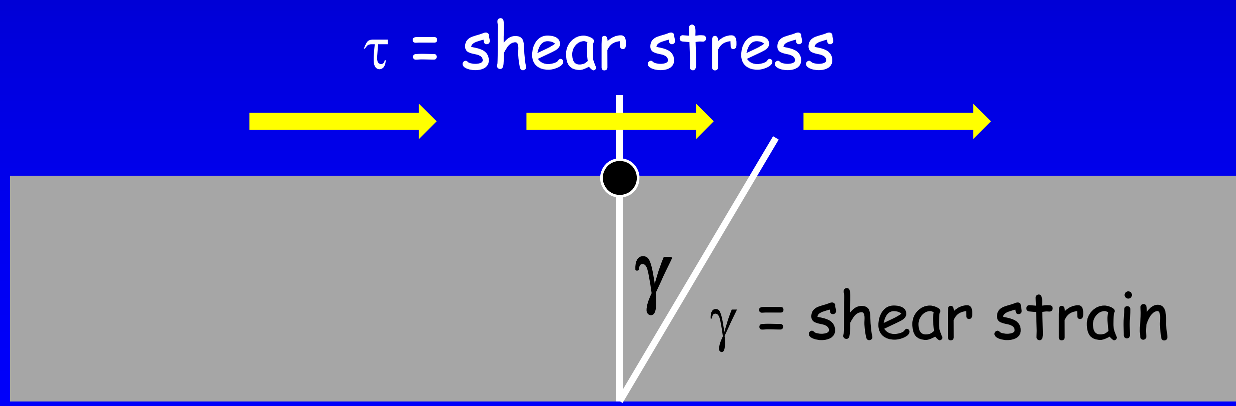
No!

Rheology of Concrete

- Rheology is the scientific description of flow
- Concrete rheometer used to determine the resistance of concrete to shear flow at various shear rates
- Concrete rheology measurements are typically expressed in terms of a flow curve that relates applied shear stress and flow rate

Flow Curve Parameters

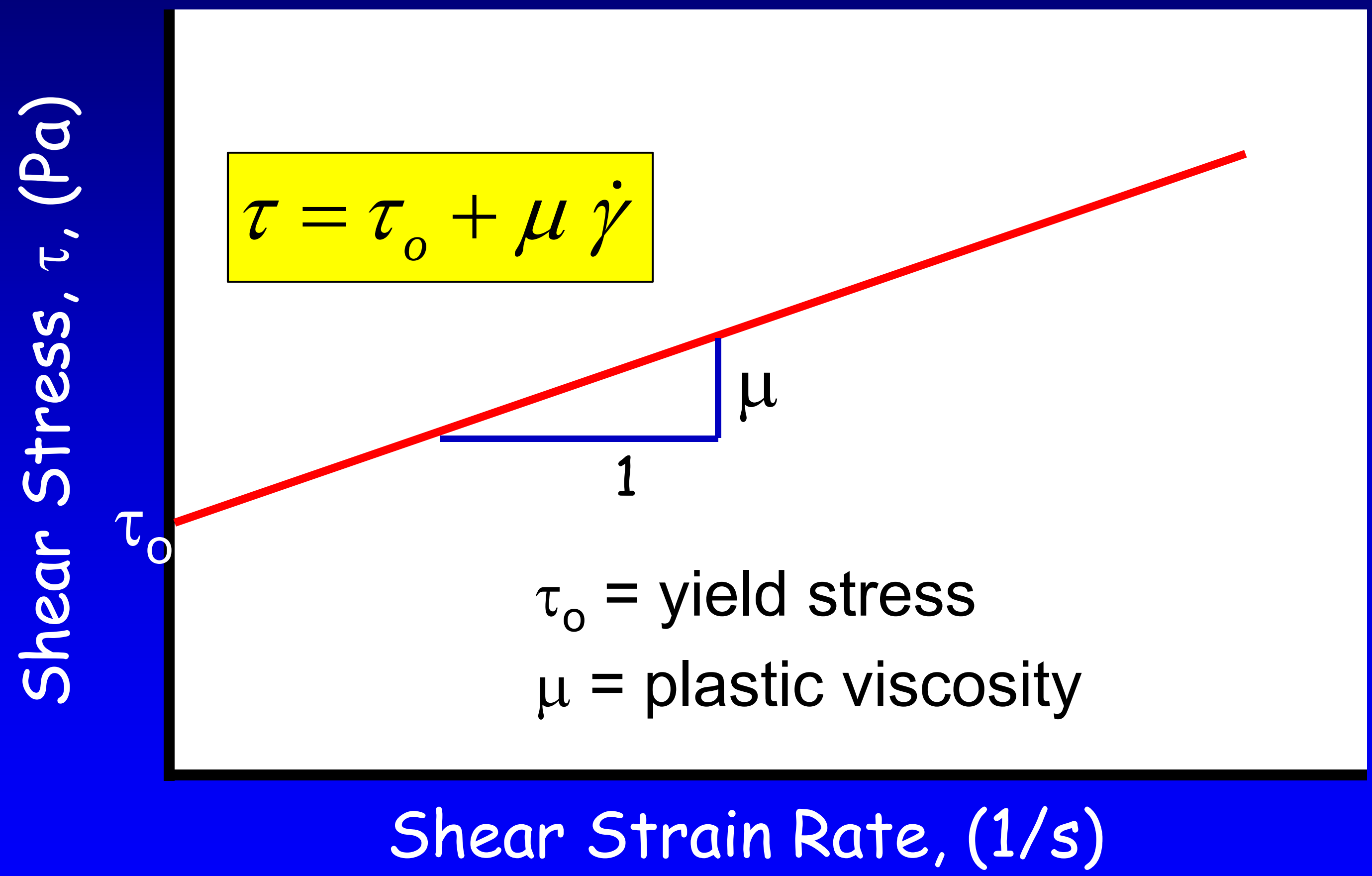
- Yield stress: the minimum shear stress to initiate or maintain constant flow (related to slump)
- Plastic viscosity: affects resistance to flow once yield stress is exceeded (related to "stickiness")



Flow:

$$\dot{\gamma} = \frac{\Delta \gamma}{\Delta t}$$

Bingham Model



Concrete Rheology

- Concrete rheology provides fundamental measurements related to concrete workability
  - Slump and slump flow are a function of yield stress and plastic viscosity
- Rheological measurements (using a rheometer) can be used to compare the fundamental properties of concrete mixtures that affect workability, finishability, and resistance to segregation

Applications

- Research and development
- Mixture optimization
- On-site quality control

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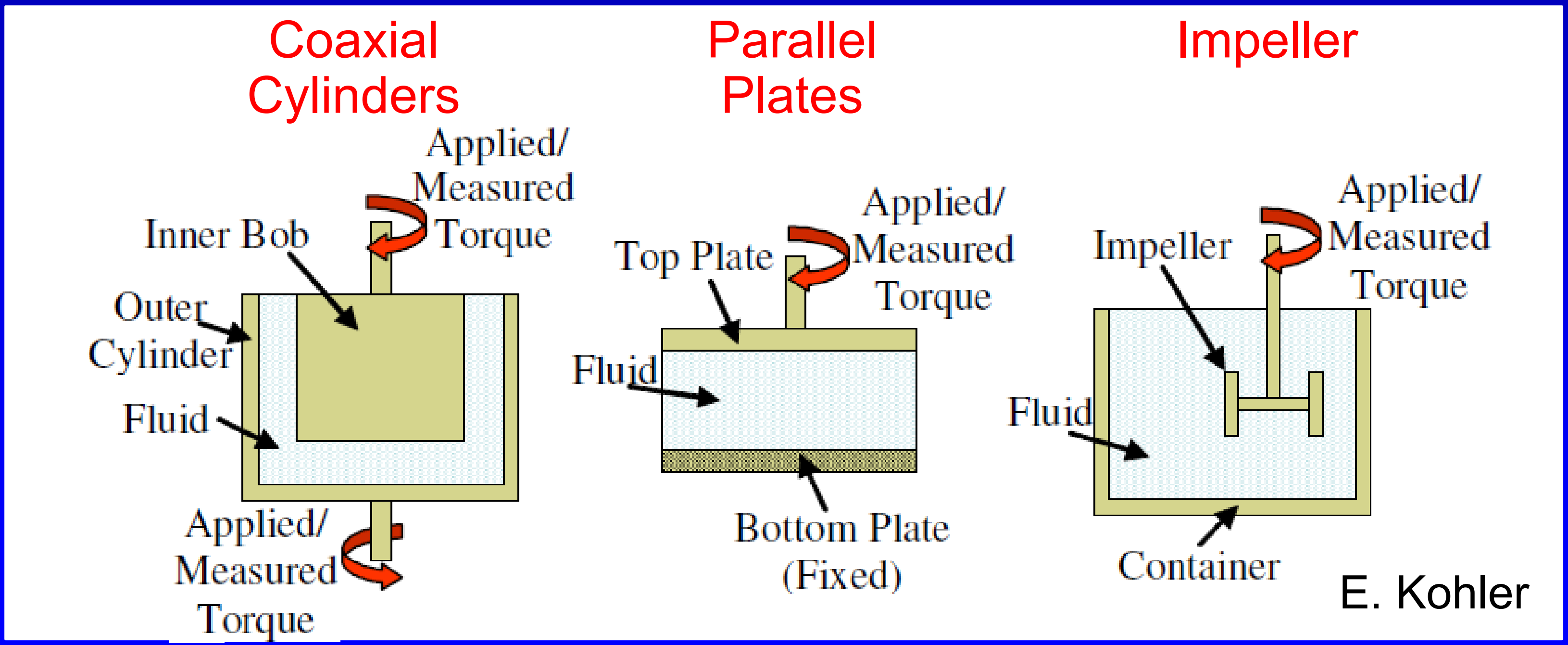
Rheometers

- Continuous shearing of concrete through rotational movement
- Results presented in terms of torque vs. rotational speed or shear stress vs. shear strain rate



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Concrete Rheometers

Tattersall Two-Point Rheometer

IBB Rheometer

ICAR Rheometer

BML Viscometer

BTRHEOM Rheometer

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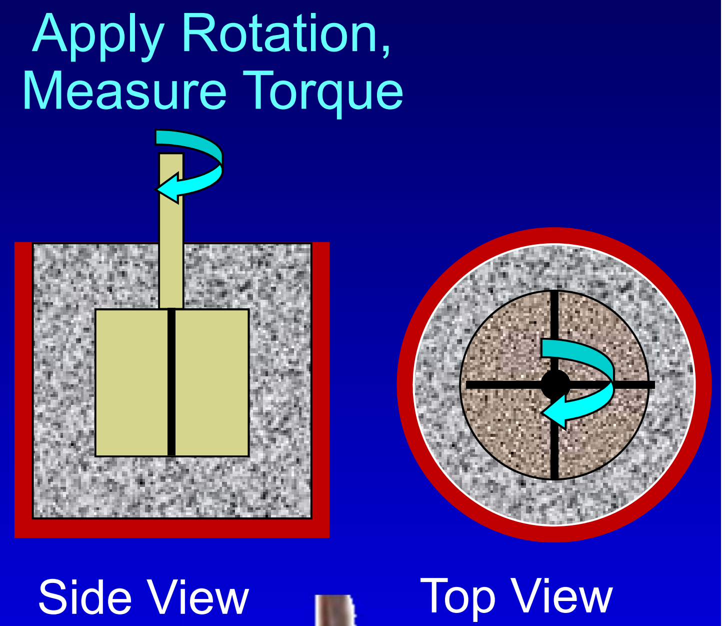
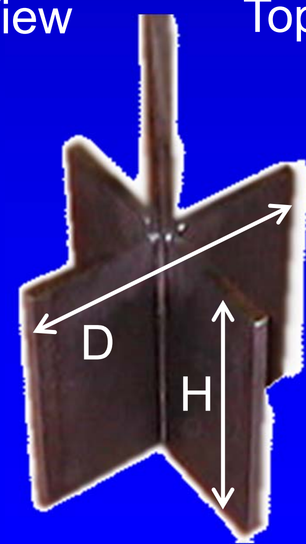
ICAR Rheometer

- Developed at International Center for Aggregates Research (UT Austin)
- Portable concrete rheometer
  - Laboratory
  - Jobsite
- Appropriate for moderately and highly flowable concretes
  - Slump greater than 3 in. [75 mm]
  - Especially well-suited for self-consolidating concrete

ICAR Rheometer

- Based on wide-gap, coaxial cylinders design
- Vane acts as inner cylinder
- Vane is rotated at different speeds
- Computer controls test and computes results
- Single test is completed in 60 seconds
  - Practical for field use





H: 5 in. [127 mm]
D: 5 in. [127 mm]

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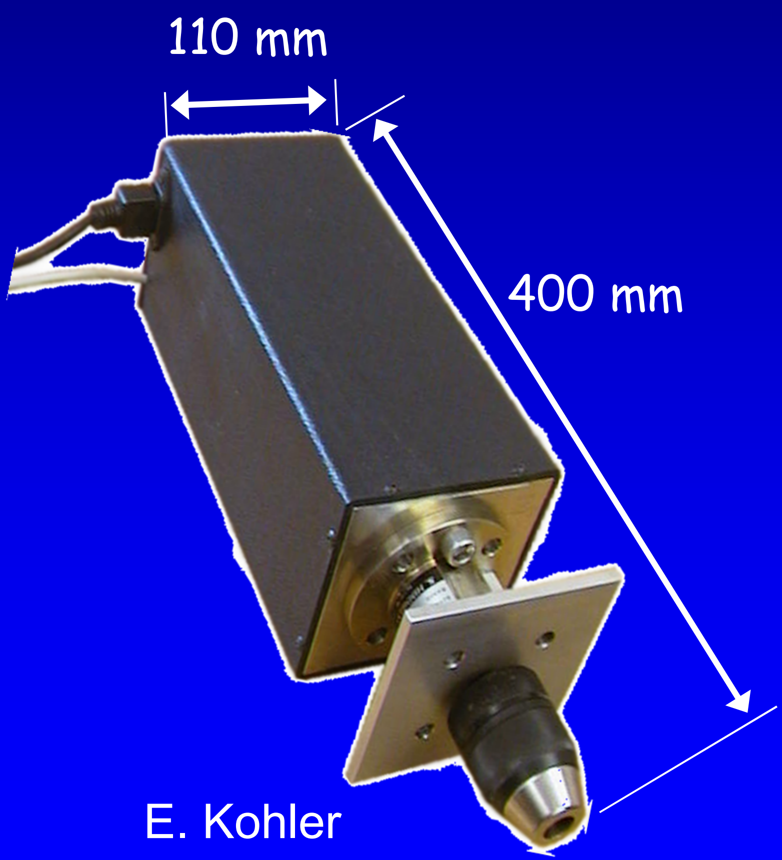
ICAR Rheometer: Portability

Rheometer: 6 kg and with accessories 18 kg



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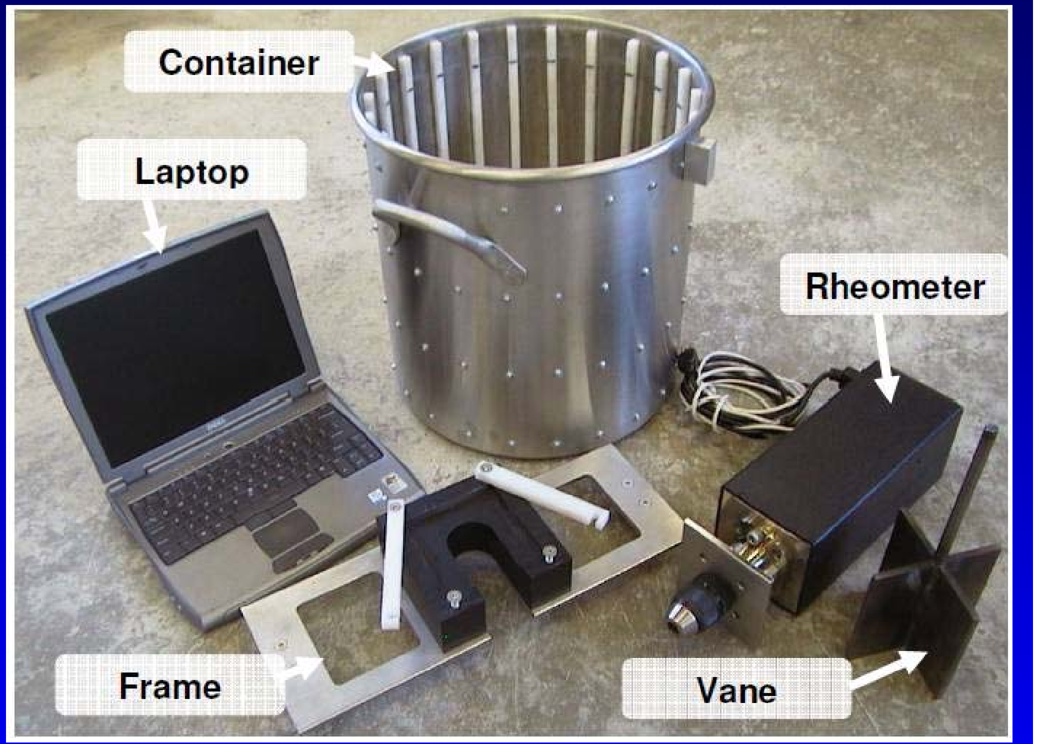


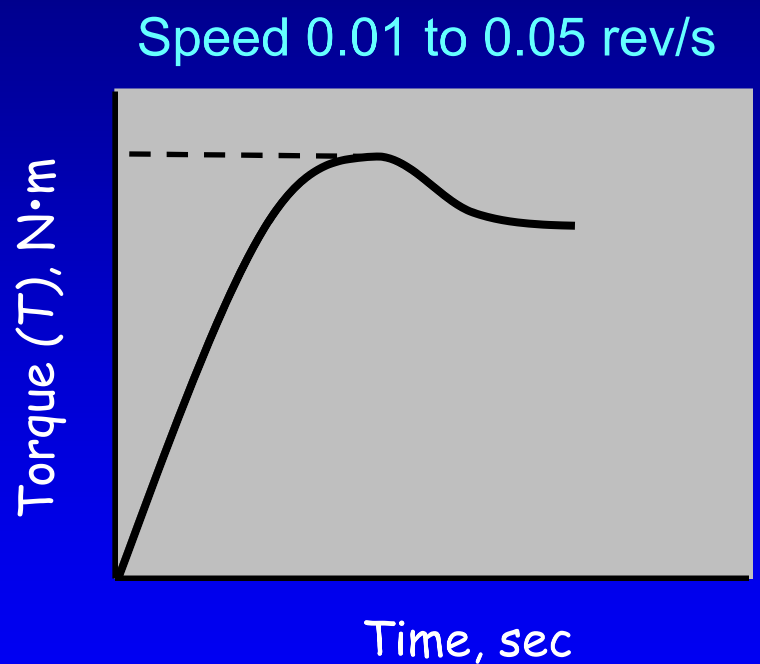
Container size depends on maximum aggregate size: for 25 mm aggregate shown

Performing Test

- Stress growth test
- Flow curve test

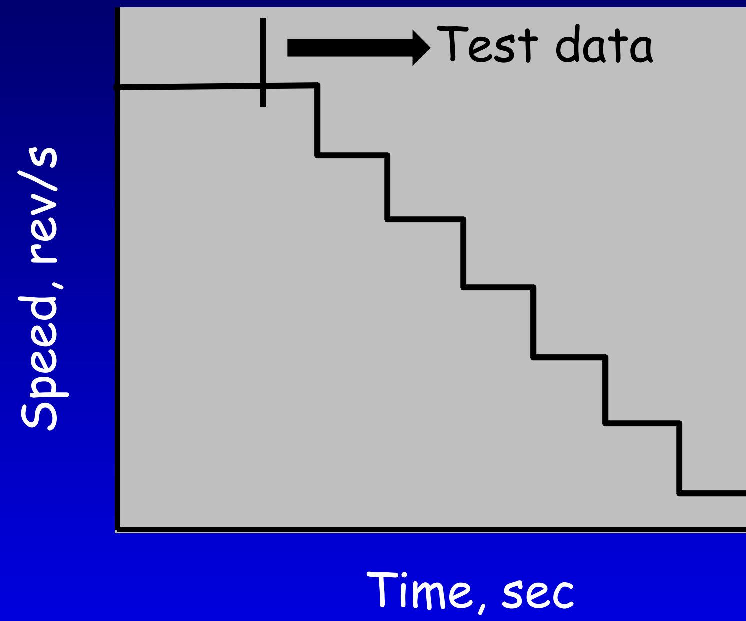
Stress Growth Test

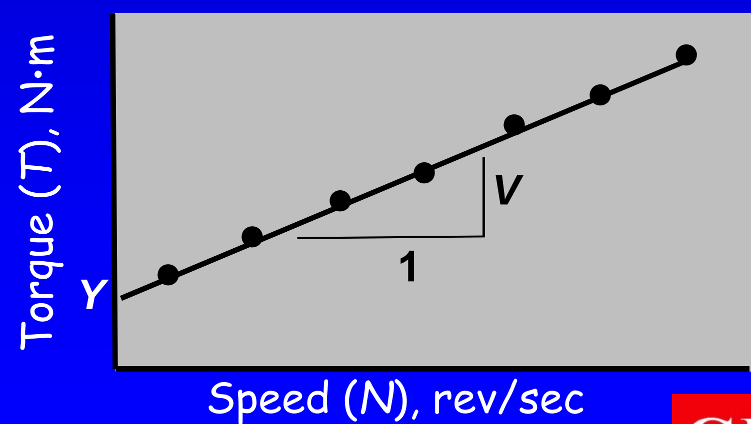
- Concrete is in "at rest" condition
- Rotate vane at a constant, slow speed while measuring increase in torque
- Torque increases with time until the initiation of flow
- From maximum torque, determine yield stress at rest (static yield stress)



Flow Curve Test

- Rotate vane at maximum speed to breakdown structure
- Reduce rotation speed in steps
- Measure average torque and speed for each step
- Determine dynamic yield stress and plastic viscosity

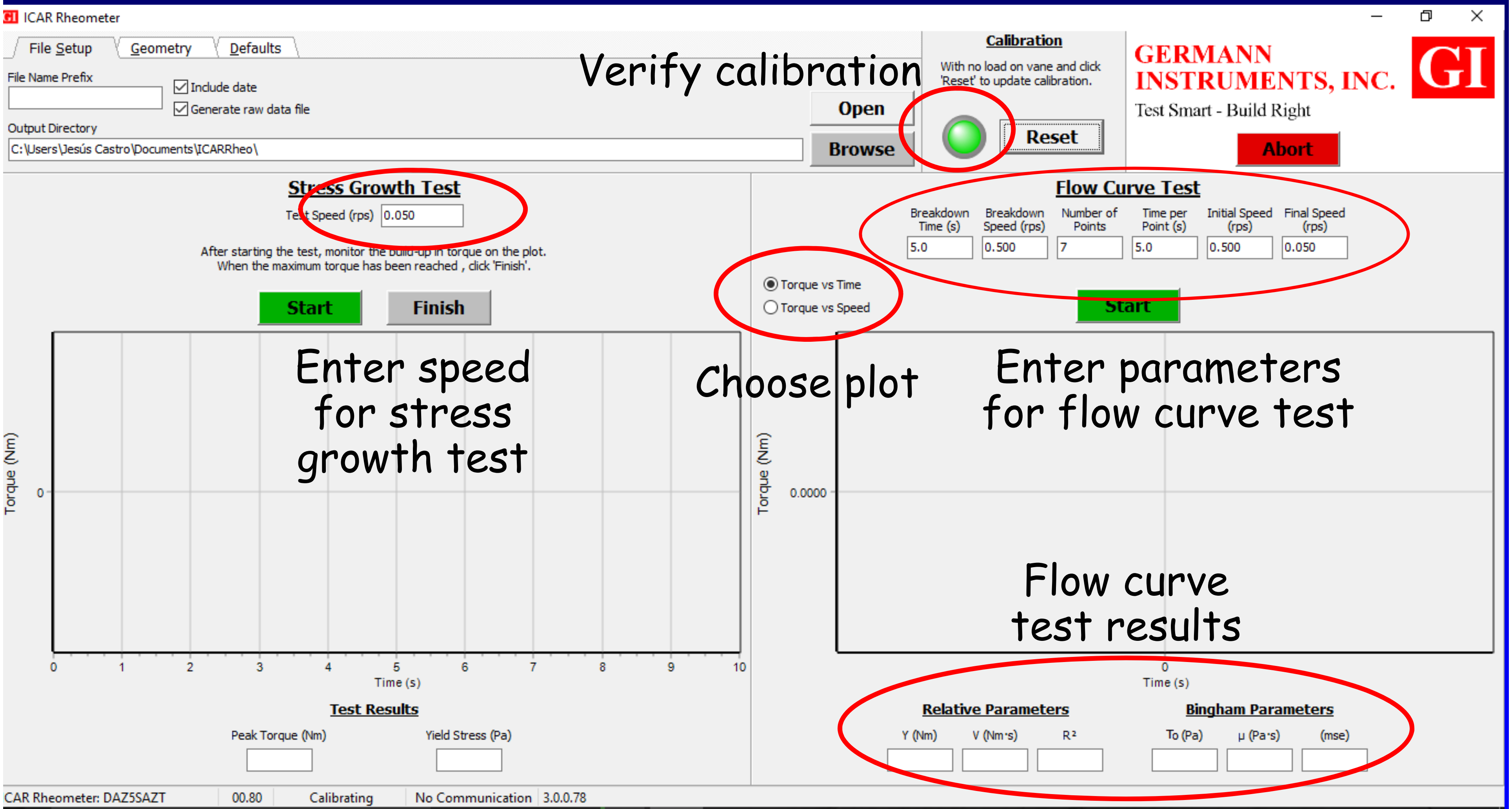




$$T = Y + V N$$

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

User Interface



Stress Growth Test

Apply constant, low shear rate, determine stress to initiate flow

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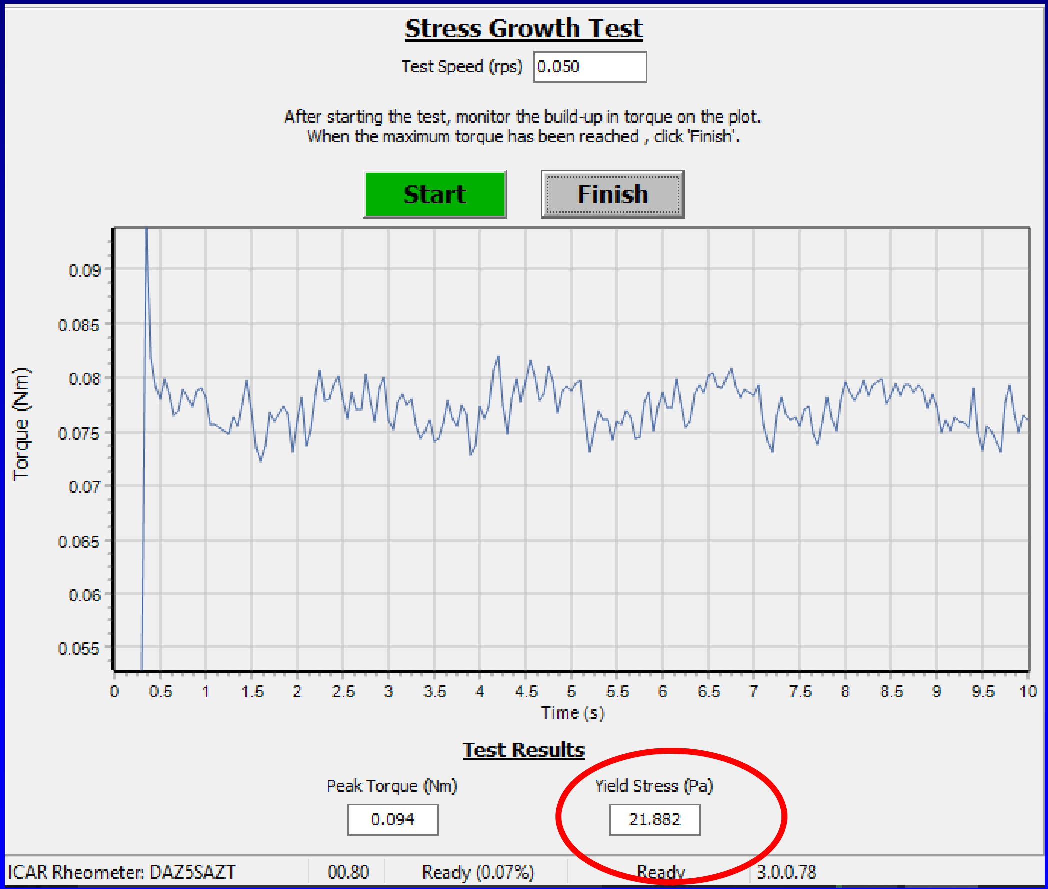
Static yield stress



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Flow Curve Test

Apply decreasing shear strain rates, measure shear stresses, and fit line

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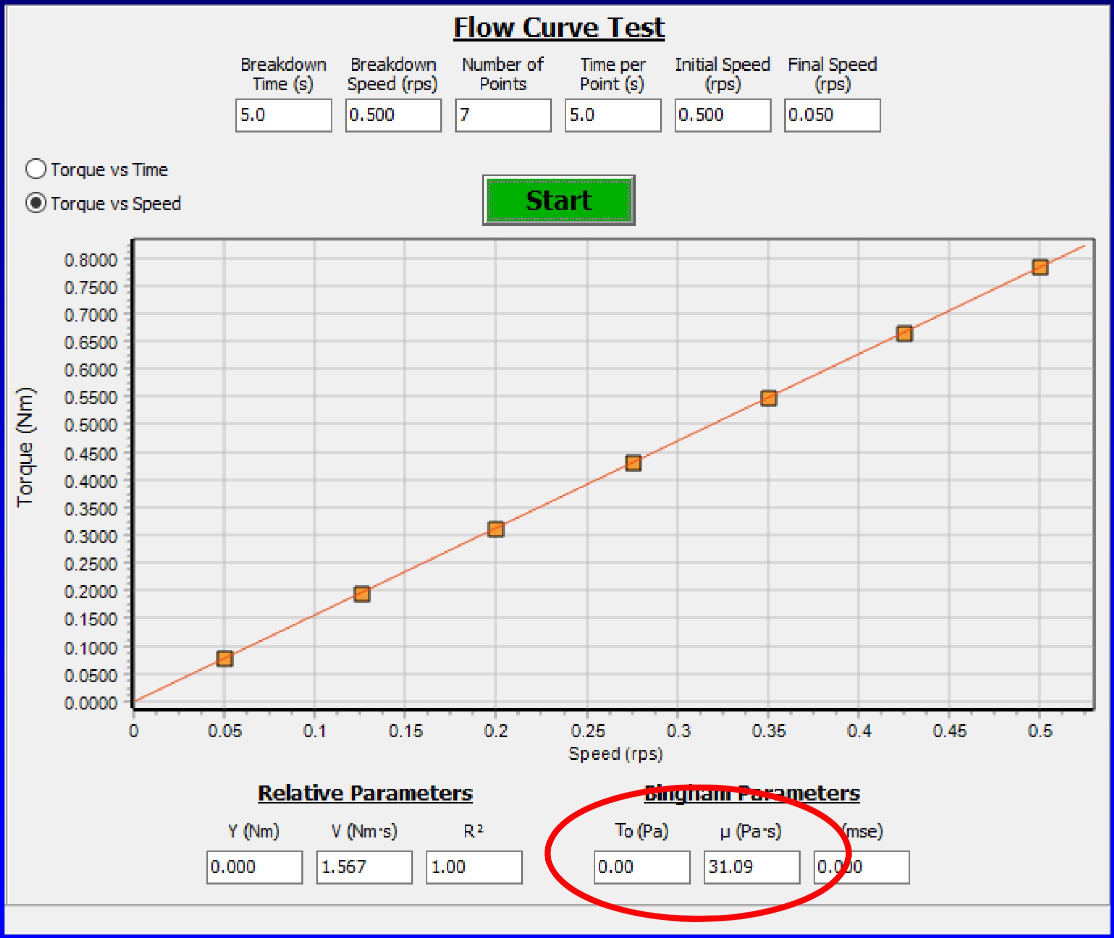
Dynamic yield stress
Plastic viscosity



Test smart – Build right

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Thixotropic Behavior

- When concrete is at rest, a weak framework develops due to van der Waals forces
    - Static yield stress represents stress to breakdown the framework and initiate flow
- After flow is initiated, less shear stress is needed to maintain flow
    - Dynamic yield stress and plastic viscosity govern flow behavior
- Static yield stress > Dynamic yield stress

A Common Thixotropic Material

- At rest: high yield stress (no flow)
- Apply shear: low yield stress (flows)
- Allow to rest: high yield stress (no flow)

Thixotropic Behavior

- Difference between static yield stress and dynamic yield stress is indicator of level of thixotropic behavior
- High static yield stress is desirable because it reduces formwork pressure
- For ease of consolidation, a low dynamic yield stress is desirable

Concrete Viscosity

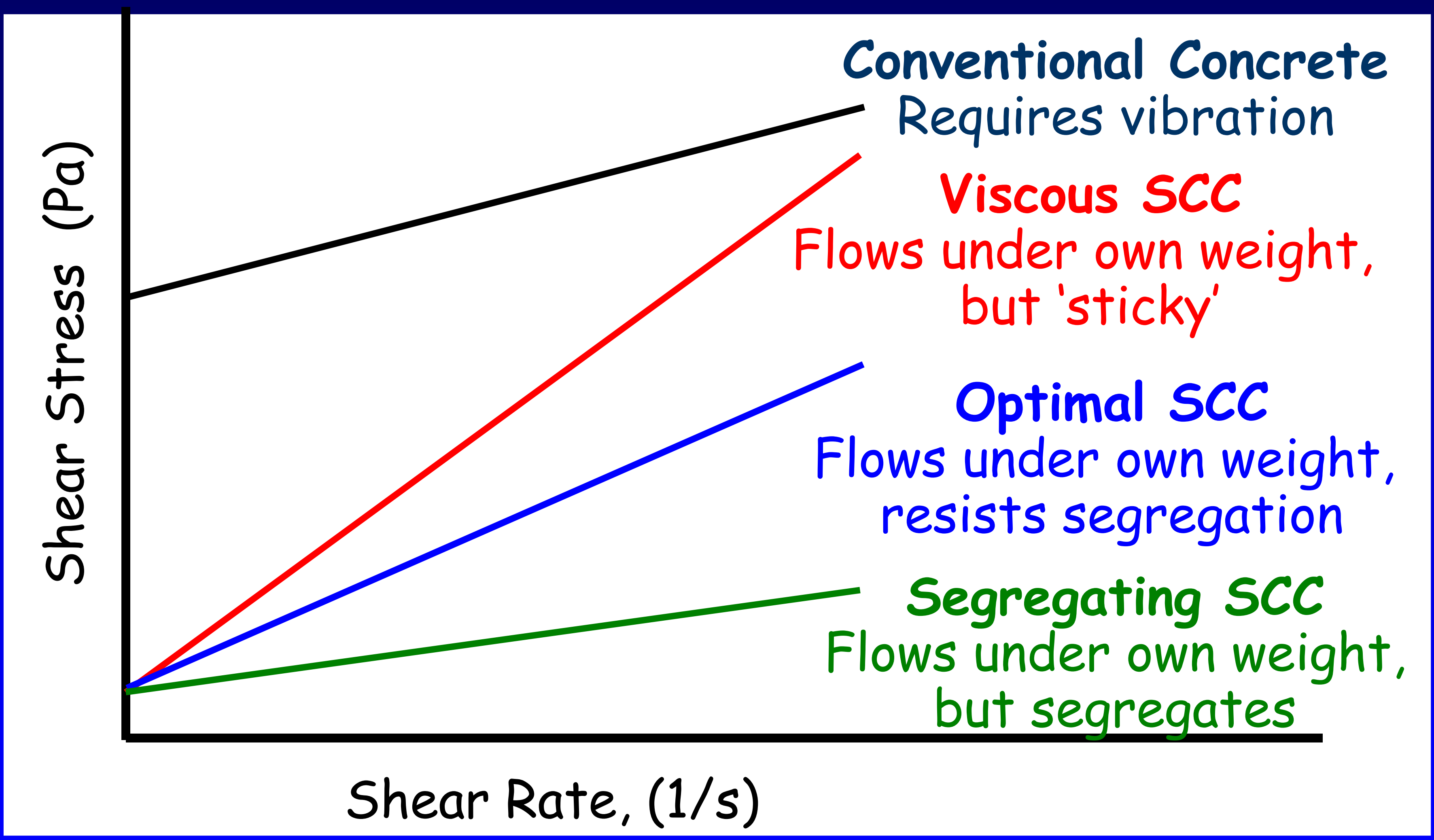
$$\tau = \tau_0 + \mu\dot{\gamma}$$

- Lower viscosity makes it easier to consolidate concrete
- High viscosity makes concrete "sticky"
- Viscosity of concrete is decreased by
  - Increasing *w/cm*
  - Using fly ash (spherical shape)
  - Good aggregate gradation
  - Using water reducing admixture
- If viscosity is too low, segregation can occur

Optimization of Rheology

- Low dynamic yield stress for ease of consolidation
- Low plastic viscosity for ease of consolidation and finishing
- Sufficient plastic viscosity to control segregation
- High static yield stress to reduce formwork pressure (weak framework when at rest)
- Especially important in design of self-consolidating concrete (SCC)

Different Flow Curves



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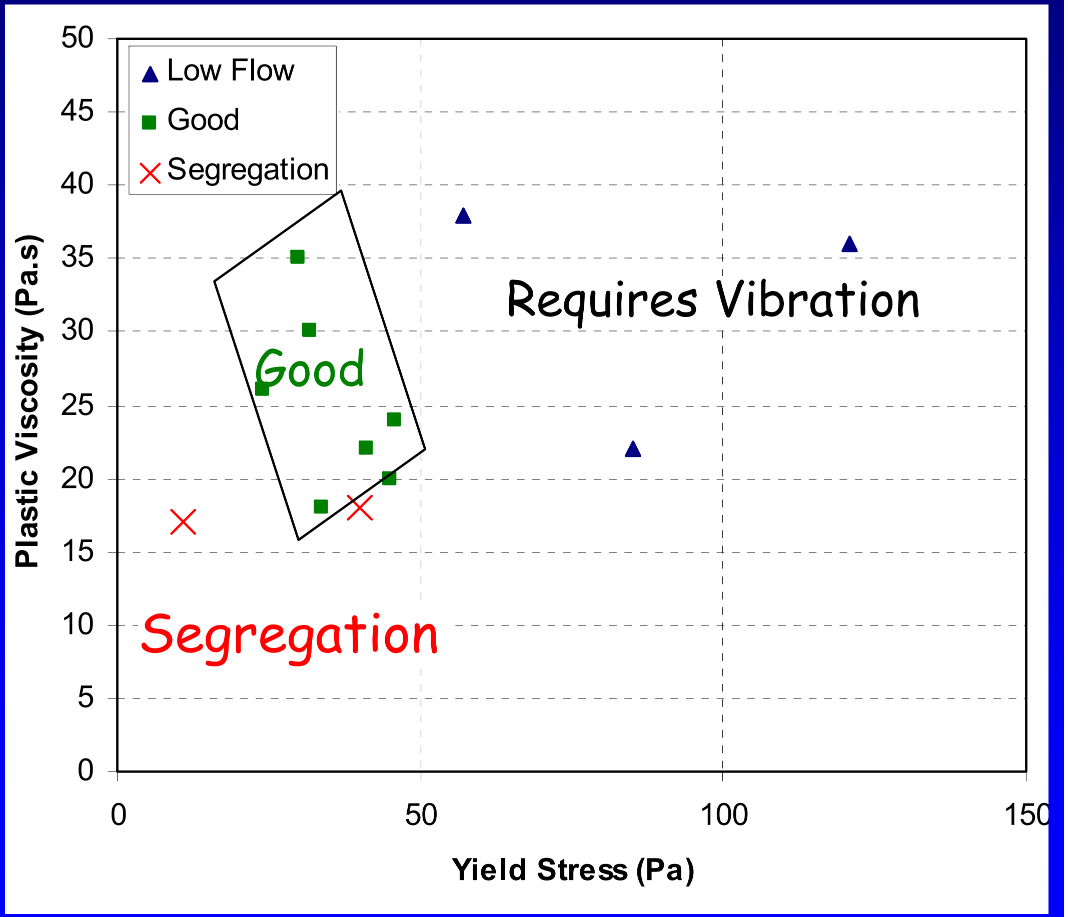
"Workability Box" for SCC

- Box shows acceptable combinations of plastic viscosity and dynamic yield stress
- Box is mixture specific
  - Acceptable properties for one mixture may not be acceptable for another
- Large box corresponds to more robust mixture



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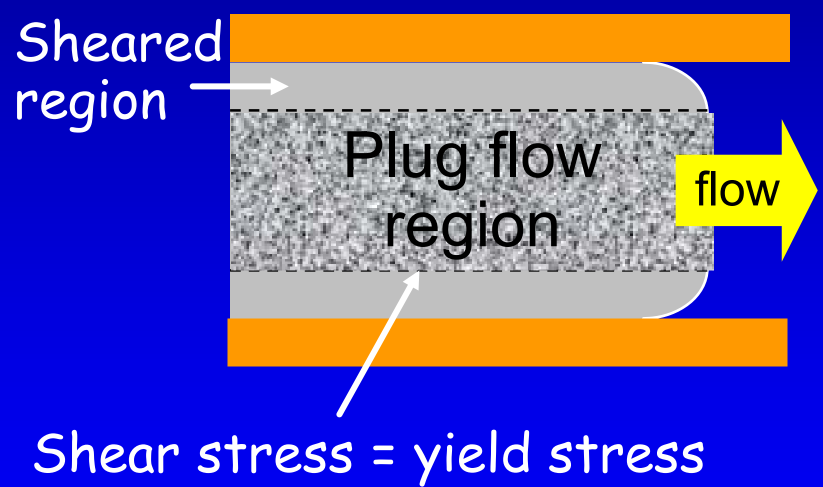
Applications: Pumpability

- Concrete moves through a pump line as a "plug" surrounded by a sheared region at the walls
  - Higher viscosity increases pumping pressure, reduces flow rate
- Pumping concrete in high-rise buildings presents unique challenges
  - High strength mixtures often have low w/cm, resulting in high concrete viscosity
  - Blockage can result in significant costs



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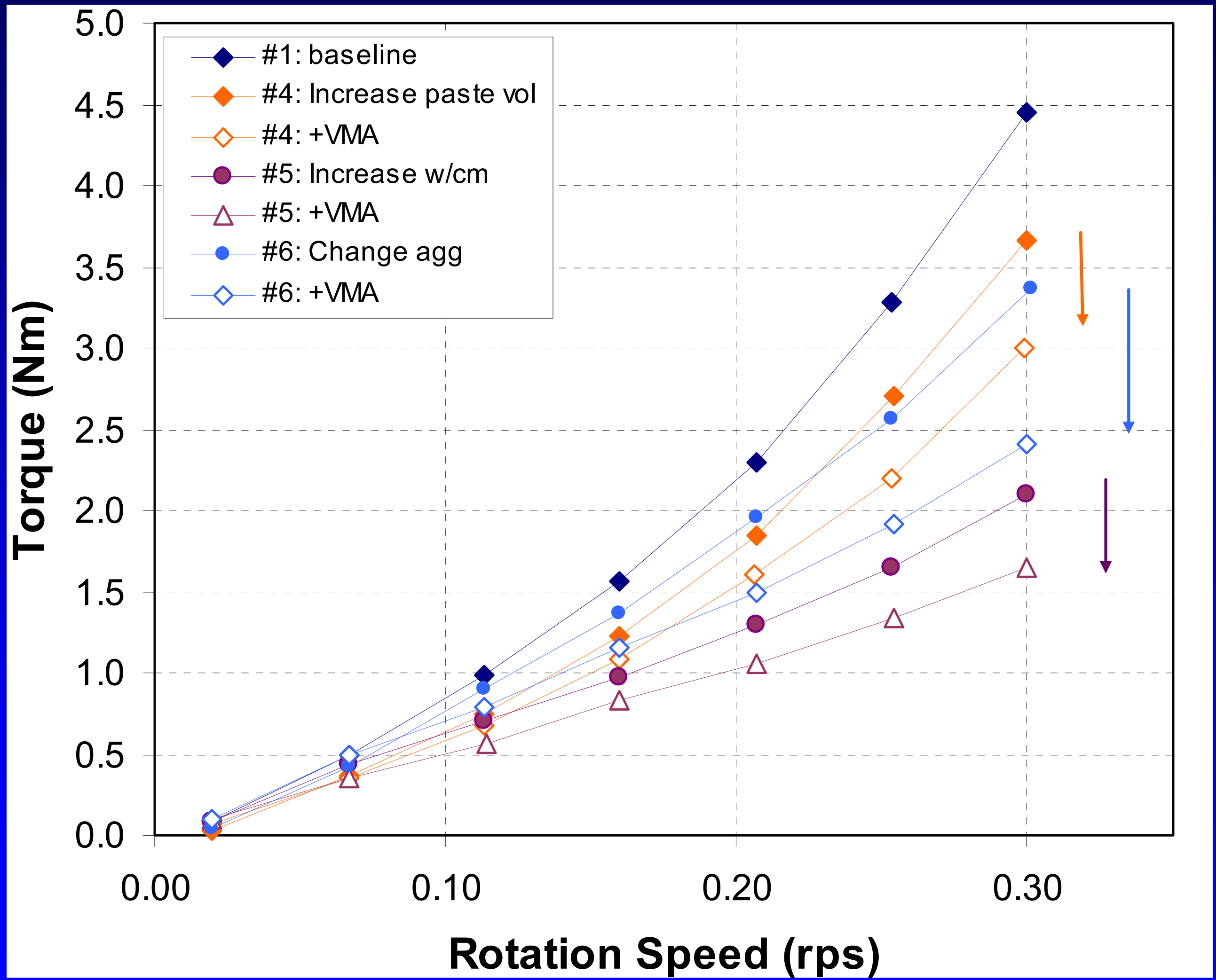
Burj Khalifa

- Pumping height 1988 ft [606 m]
- Concrete volume in lines: 14 yd^3 [11 m^3]
- Travel time: 40 minutes

3000 psi
20 MPa

Making Pumpable Mixtures



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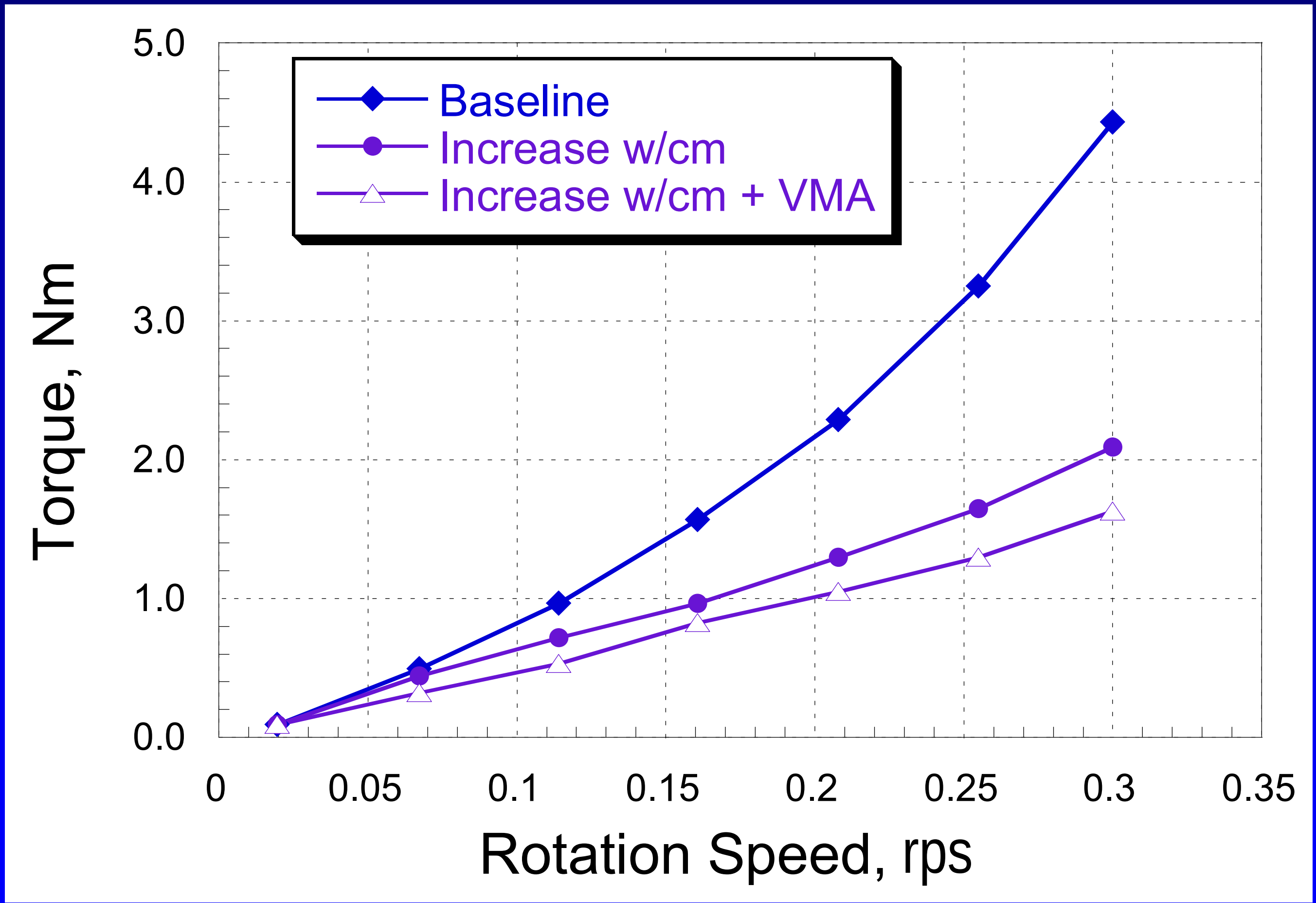
Making Pumpable Mixtures

Increase w/cm + VMA



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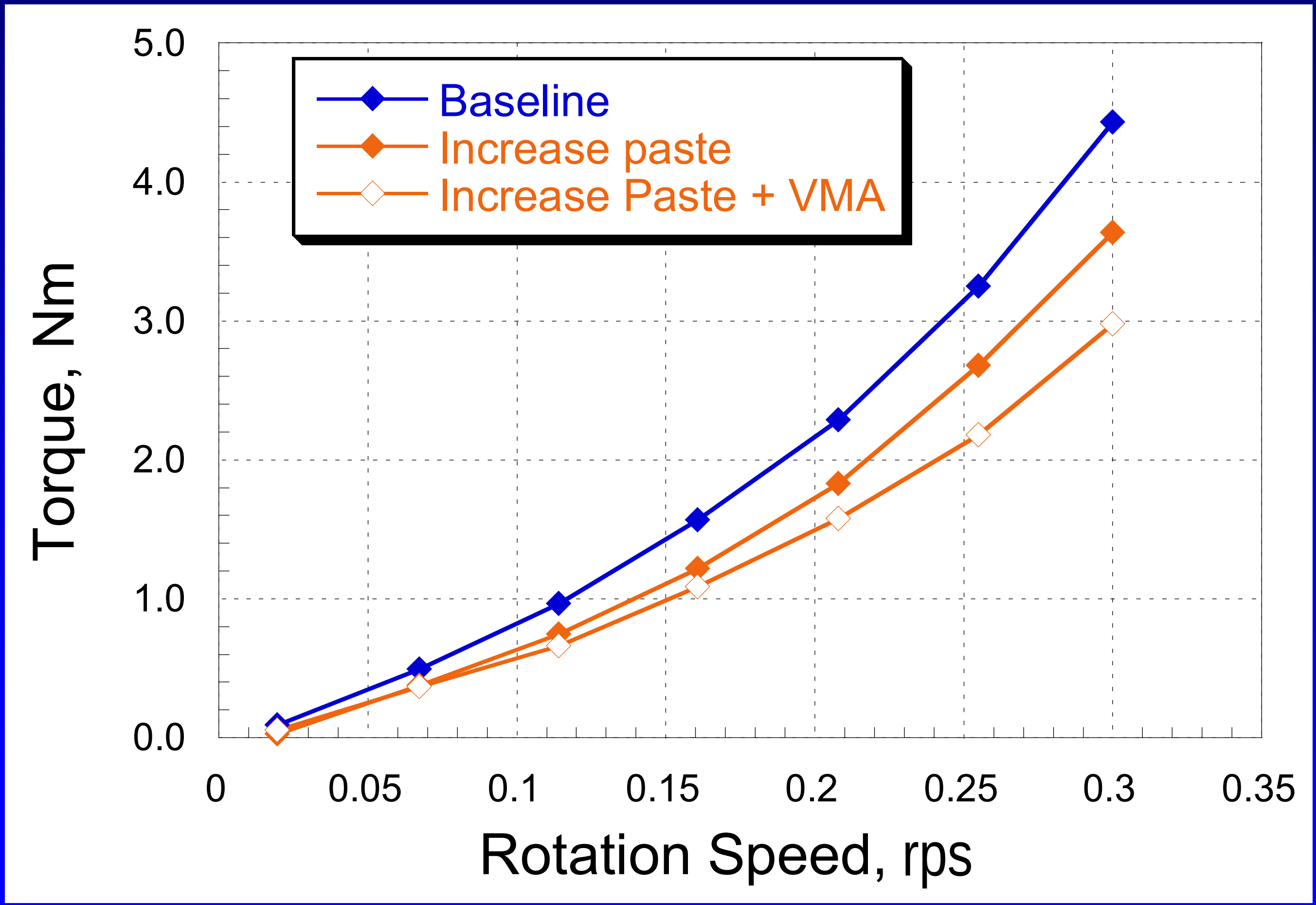
Making Pumpable Mixtures

Increase Paste Content + VMA



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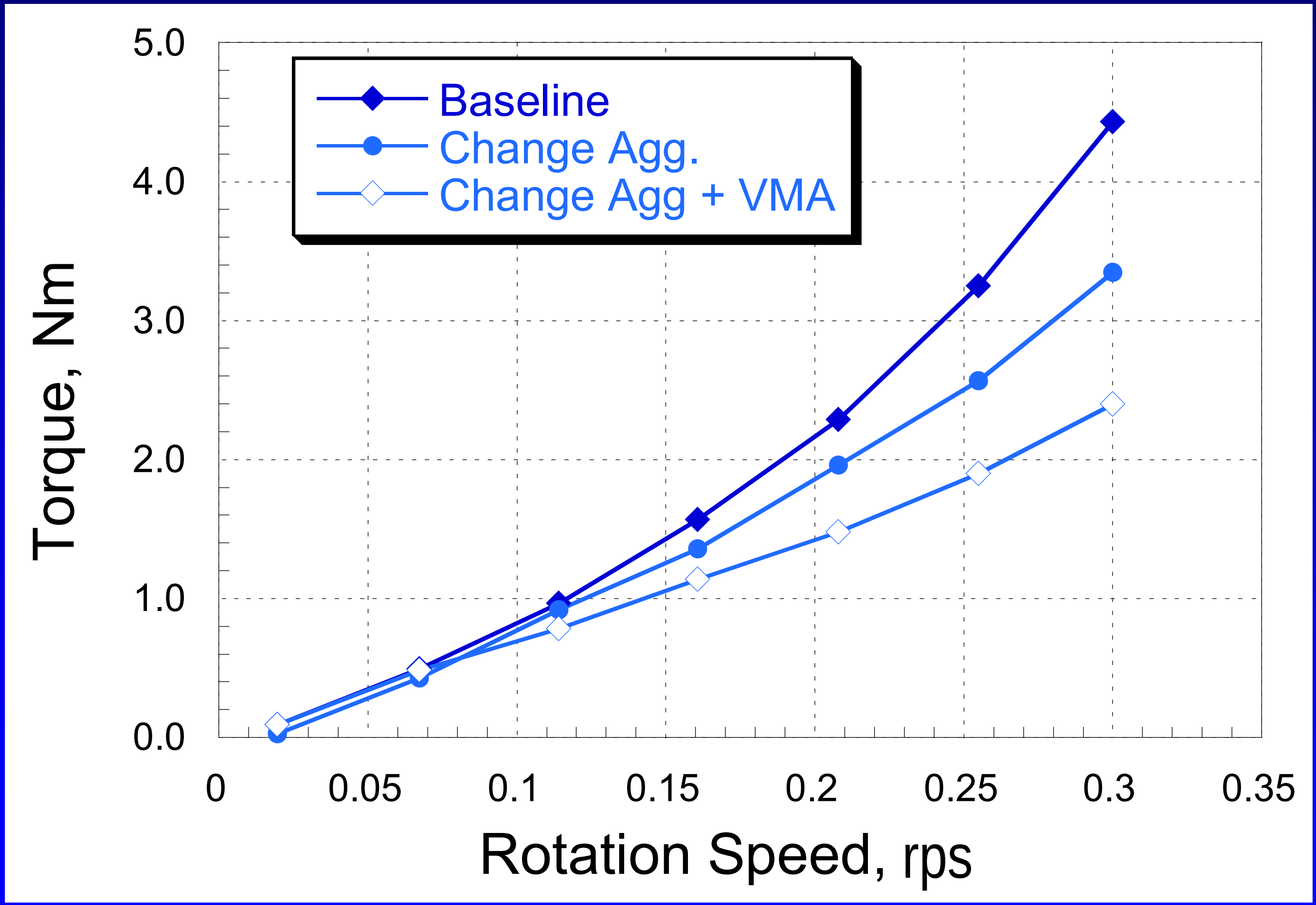
Making Pumpable Mixtures

Change Aggregate



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Summary

- Concrete rheology provides a scientific description of flow behavior (quantify workability)
- Yield stress and plastic viscosity are the key parameters to describe concrete rheology
  - Can be optimized for different applications
- ICAR Rheometer provides a practical tool for measuring concrete rheology
  - In laboratory for mixture development
  - In field for quality control