고성능 콘크리트 공학

High Performance Concrete Engineering

〈Fresh Properties〉

문주혁 조교수
Assistant Prof. Juhyuk Moon

Fresh Concrete

- Two sets of criteria to consider when making concrete
  - Short-term requirements – workability
  - Long-term requirements – strength, durability, volume stability

- Fresh concrete must be capable of satisfying the following requirements
  - Easily mixed and transported
  - Uniform throughout a given batch and between batches
  - Have flow properties to fill the forms completely
  - Easily compacted without applying excessive energy
  - No segregation during placing and consolidation
  - Easily and properly finished

Workability

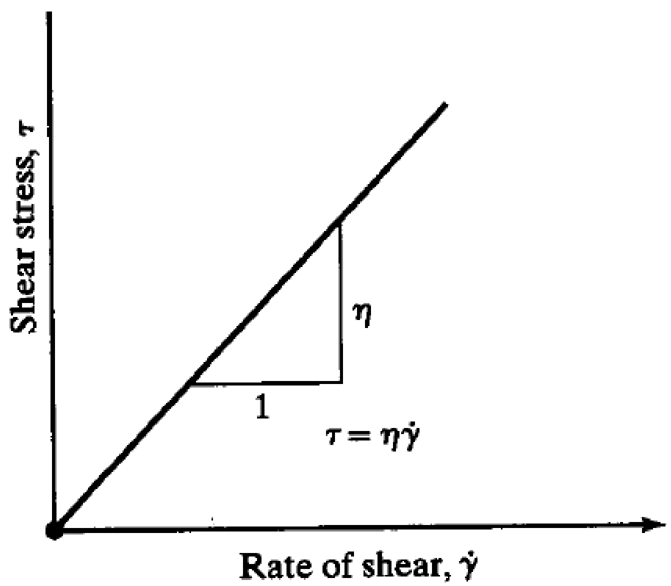
- Commonly used terms
  - Consistency, flowability, mobility, pumpability, compactibility, finishability, harshness
  - Subjective and qualitative

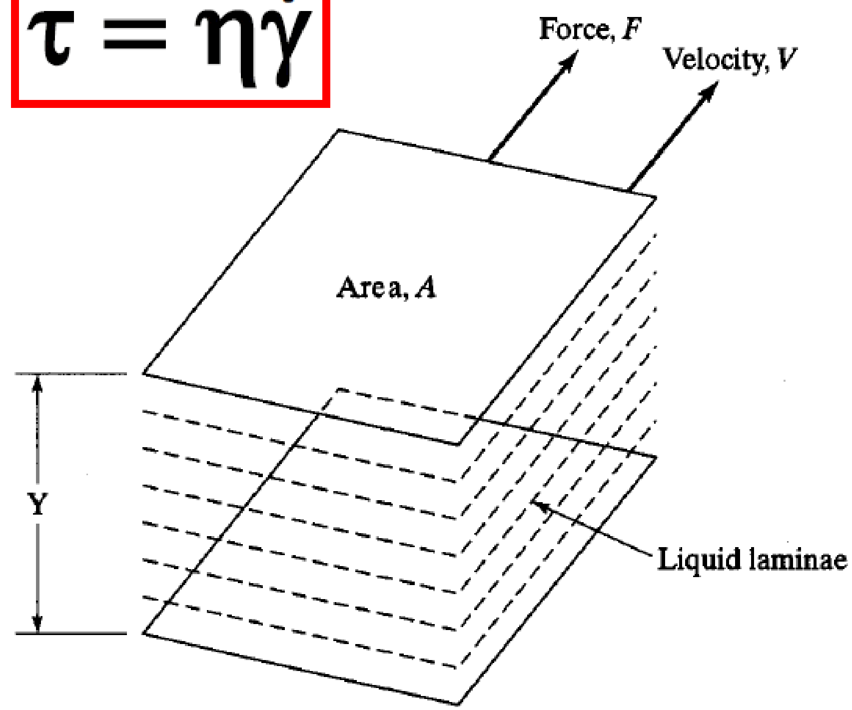
- "Workability"
  - used to represent all the above
  - defined in terms of the amount of mechanical work or energy required to produce full compaction of concrete without segregation

Basic Principle of Rheology

- Rheology
  - dealing with deformation and flow of materials under stress
- Newton's law of viscous flow
  - Derived by considering the shearing of adjacent layers of liquid

$$\tau = \eta\dot{\gamma}$$





Shear stress, $\tau = \frac{F}{A}$

Rate of shear, $\dot{\gamma} = \frac{dV}{dY}$

Coefficient of viscosity, $\eta = \frac{\tau}{\dot{\gamma}}$

- Valid for **dilute suspension of solid in liquid** with no inter-particle forces
- Single-point test

(Mindess et al 2003)

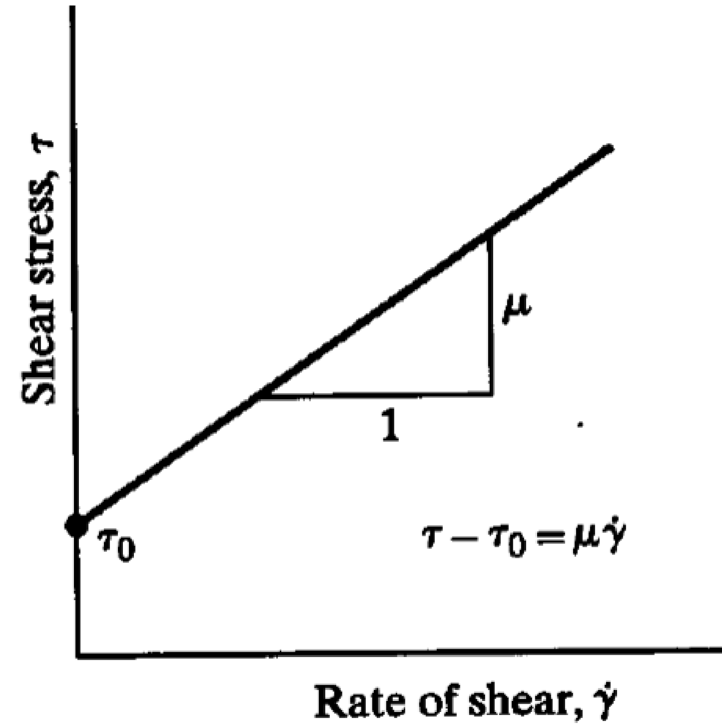
Basic Principle of Rheology

- Fresh concrete has a shear strength which must be exceeded before flow can occur
- Bingham model

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

where τ_0 = yield stress

μ = plastic viscosity



– Two- point test to determine τ_0 and μ

– Single - point tests of workability current in use do not adequately quantify the flow behavior of fresh concrete

(Mindess et al 2003)

Factors Affecting Workability

- Water content, mix proportions, aggregate properties, time, temperature, characteristics of cement, & admixtures

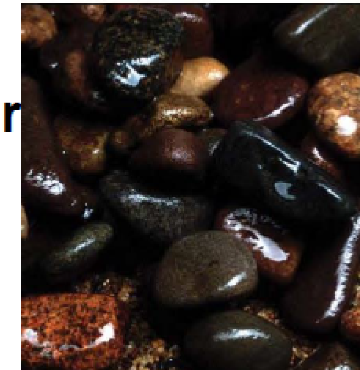
- Water content
  - For a given maximum size of coarse aggregate and aggregate grading, the workability is a direct function of water content
    - concrete with very high workability tends to segregate and bleed
    - concrete with too low workability may be difficult to place and compact
  - Finer particles require more water, but minimum quantity of fine material is essential to achieve "plasticity"

Factors Affecting Workability

- Influence of aggregate
  - Amount of aggregate
    - For a constant w/c, ↑ aggregate/cement will ↓ workability
  - Relative proportions of fine and coarse aggregate
    - For finer aggregate grading, more cement is needed
    - If fine aggregate is not sufficient → harsh concrete
    - Excess fine aggregate → more permeable concrete
  - Shape and surface texture
    - Nearly spherical particles will increase workability
    - Smooth particles tend to increase workability
  - Porosity
    - Free water content – contribute to workability
    - Total water content – including free water and water absorbed by aggregate

) Aggregates from crushing

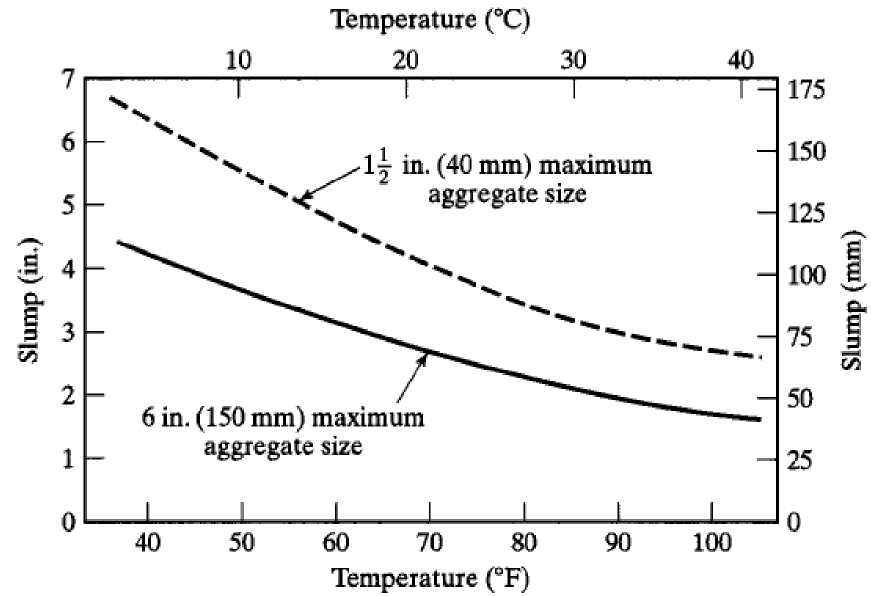
) River gravel



Factors Affecting Workability

- **Temperature**
  - Ambient temperature ↑, workability ↓

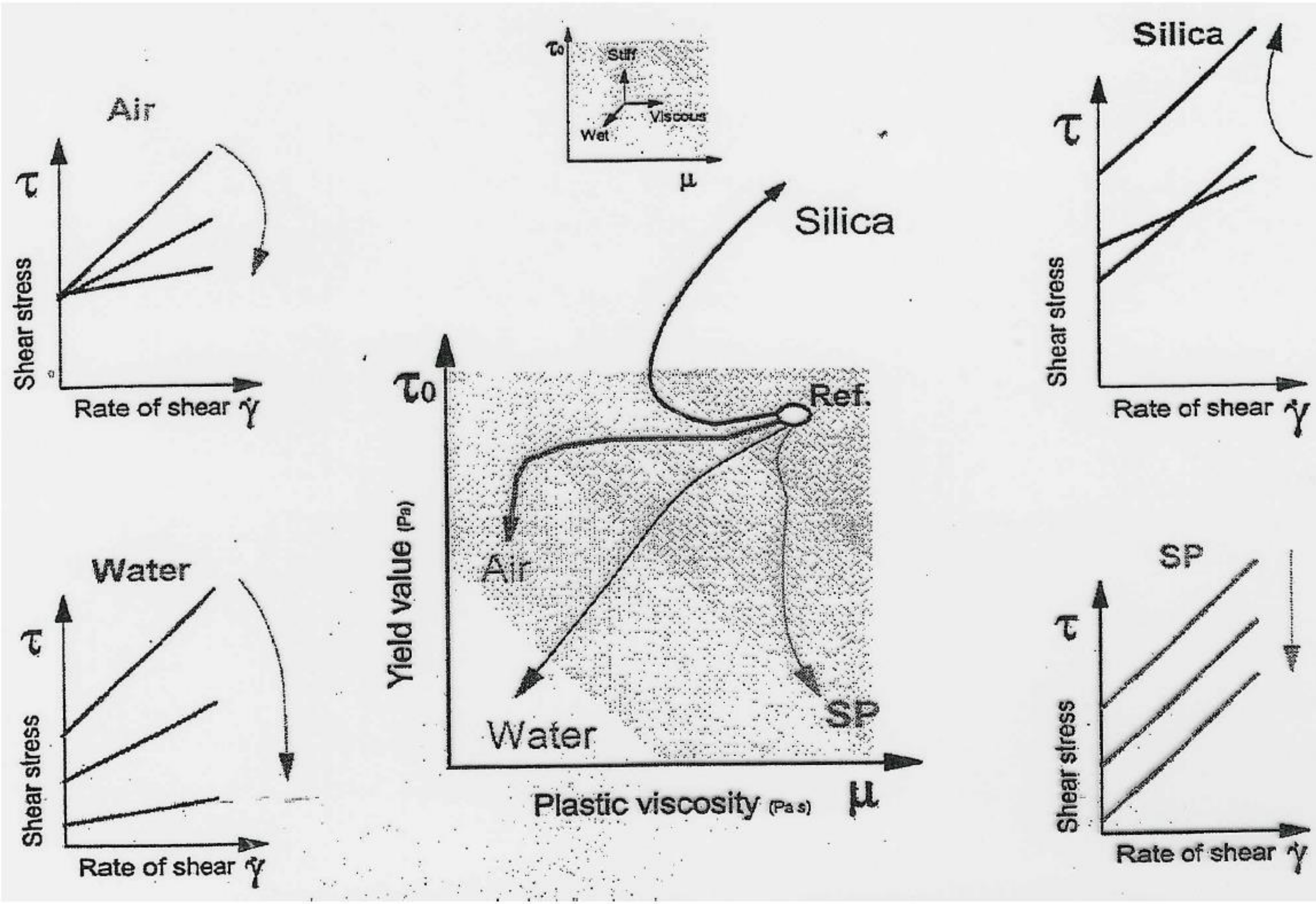
(Concrete Manual, US Bureau of Reclamation 1975)



- **Cement**
  - Less important than aggregate
  - Increased fineness will reduce workability at given w/c
  - In normal concrete, at a given water content
    - too low cement content produce harsh mixtures → poor finishability
    - too high cement content or a very fine cement show good cohesiveness, but tends to be sticky

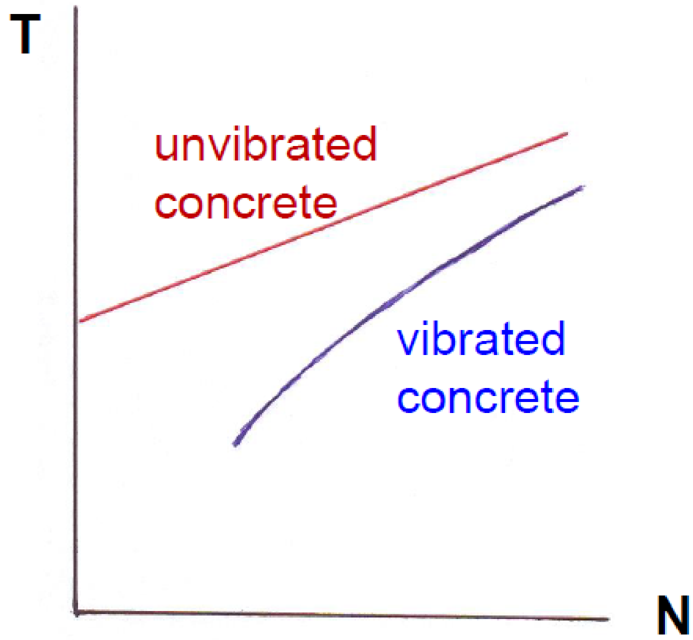
Factors Affecting Workability

- Admixtures
  - Mineral admixtures
    - Improve the cohesiveness (If they are used as cement replacement, may have little effect on flowability)
    - Fly ash
      - Spherical shape acting as ball bearings
      - Reduce water requirement for given slump
      - Increase slump for given water content and w/cm
    - Silica fume
      - High specific surface
      - Increase water requirement
      - Superplasticizers are often used in combination with SF
    - Slag
      - Effect on workability is not significant
  - Air-entraining and water-reducing admixtures
    - Improve workability

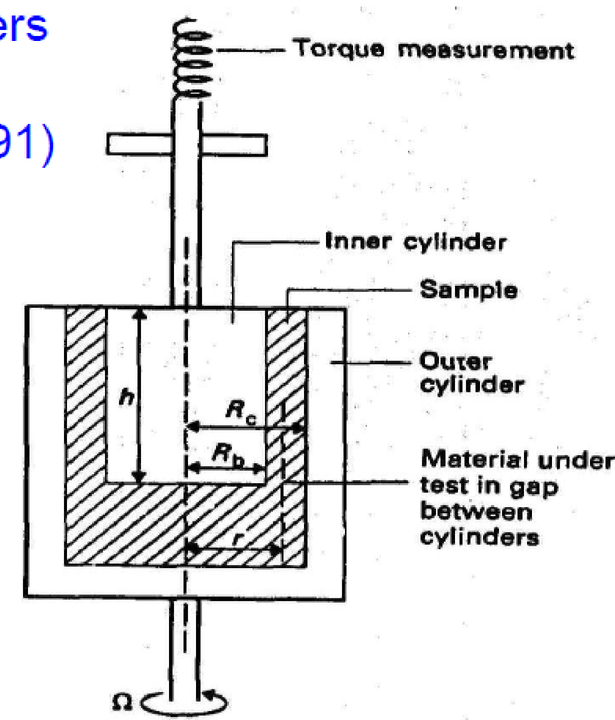


(Wallevik 1990)

Effect of vibration on concrete flow curve



Principle of the coaxial cylinders viscometer (Tattersall, 1991)



T = g + hN

where

N – rotational speed, corresponds to shear rate γ'

T - measured torque at N, corresponds to shear stress τ,

g - intercept, corresponds to yield stress τo

h - gradient of the relationship, corresponds to viccosity

Factors Affecting Workability

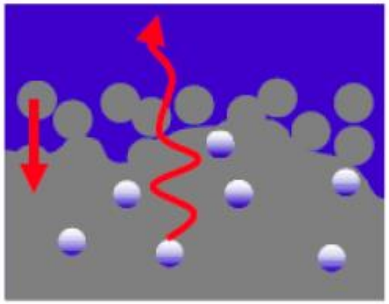
- Time
- Loss of workability
  - Slump loss is a normal phenomenon in all concrete
  - Slump loss occurs when the free water from a concrete mixture is removed by
    - hydration reaction
    - adsorption on the surface of hydration products
    - evaporation
  - The slump loss is approximately linear with time
    - Greatest in the first 0.5 – 1 hr after mixing
    - Thereafter, the rate of slump loss is determined mainly by
      - elapsed time, temperature, cement composition, admixtures

Factors Affecting Workability

- Loss of workability (cont'd)
  - Significance
    - "hang-up" of concrete within the drum of truck mixer
    - difficulty in pumping and placing concrete
    - extra labour needed in placement and finishing
    - loss of strength, durability, and other properties when retempering water is excessive or is not mixed properly
  - How to overcome the slump loss
    - starting with higher initial slump
    - add extra admixtures at job sites

Segregation and Bleeding

- **Segregation** - separation of the components of fresh concrete so that they are no longer uniformly distributed
  - separation of coarse aggregate from concrete
    - Concrete too wet
    - Concrete too dry
  - separation of water from concrete - bleeding
- **Bleeding**
  - Upward movement of water after concrete has been placed and compacted but before it has set

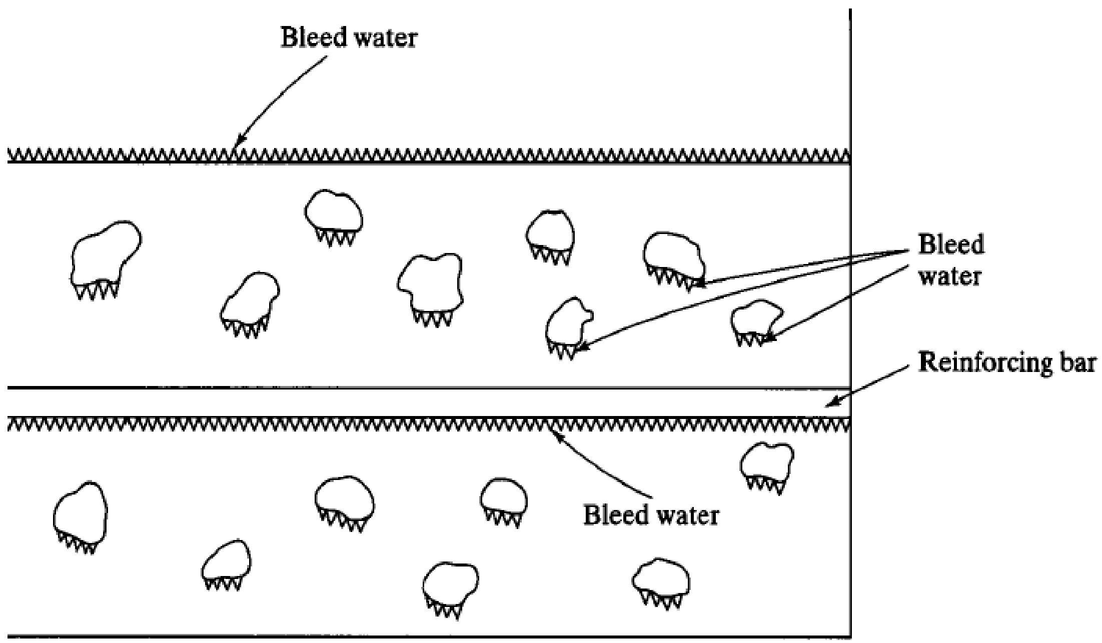


Bleeding

Segregation

Segregation and Bleeding

- Significance
  - Segregation: It is impossible to achieve full compaction after a concrete has segregated. Affect strength, durability.
  - Bleeding: The upper portion of concrete is weaker than the concrete in the lower portion
    - under reinforcing bars
    - under coarse aggregate



(Mindess et al 2003)

Segregation and Bleeding

- **Cause**
  - Excessive amount of large particles of coarse aggregate with either too high or too low density
  - Insufficient fine particles
  - Mixes that are either too wet or too dry
  - Over vibration
- **Control**
  - Segregation of coarse aggregate
    - Pay attention to aggregate grading, reducing max aggregate size, use more sand or a finer sand
    - Use mineral admixtures, air entraining admixture
  - Bleeding
    - Use mineral admixtures
    - Use air - entraining admixture
    - Reduce water content while maintaining workability

Measurement of Workability

- It has been suggested that workability should measure
  - Compactibility
  - Mobility
  - Stability

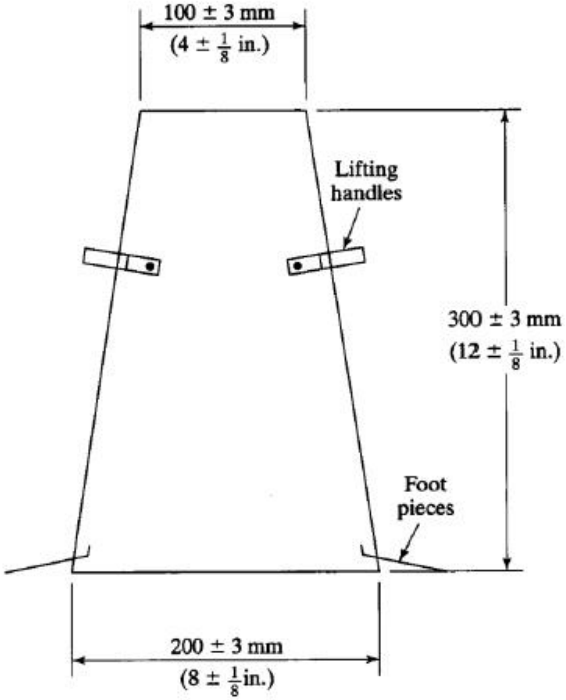
Recommended ranges for test methods as in BS 1881

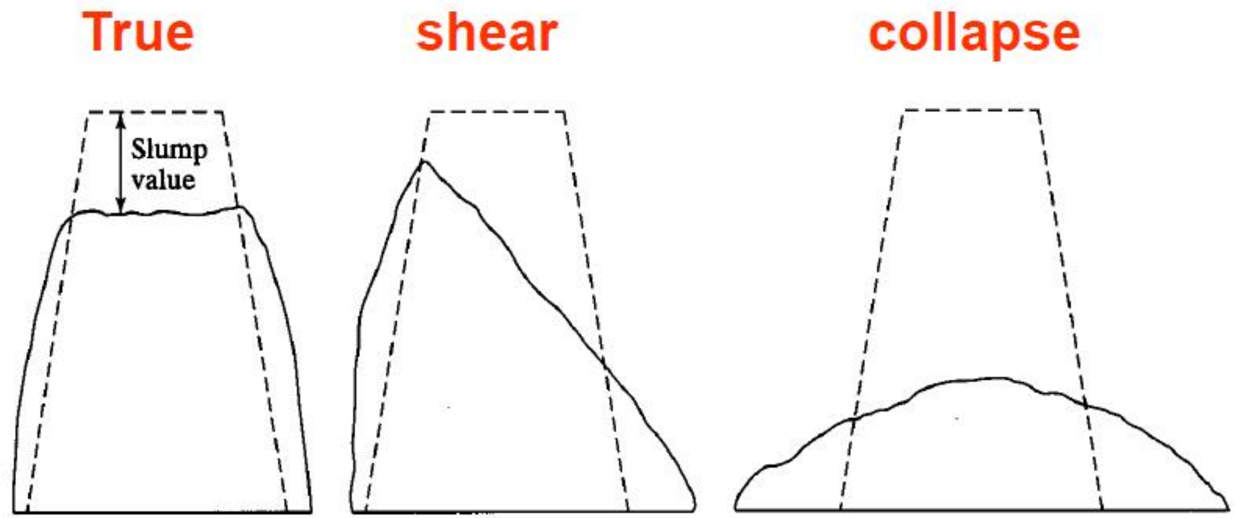
Workability	*Method*
Very low	Vebe time
Low	Vebe time, compacting factor
Medium	Compacting factor, slump
High	Compacting factor, slump, flow
Very high	Flow

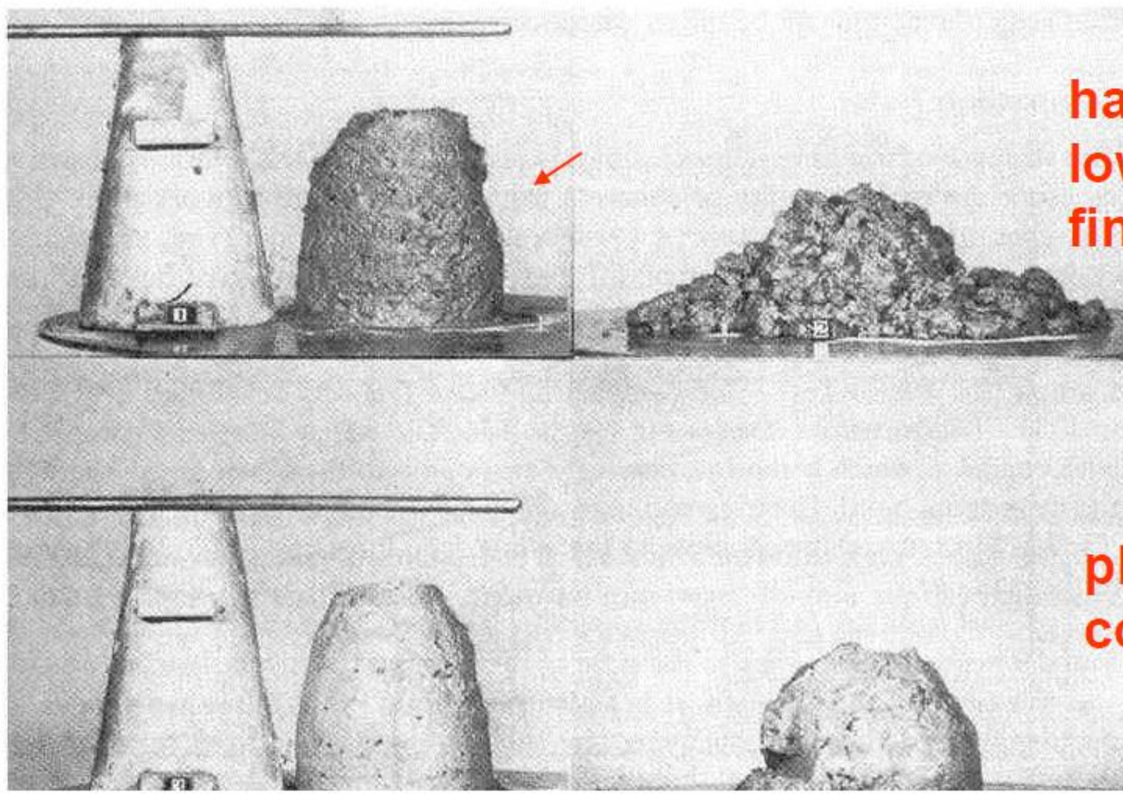
- Standard test methods
  - Empirical methods
  - “Single” point tests
  - Cannot easily be compared to one another
  - Provide information on variations in workability, quality control
  - Individual method applicable to a certain range of workability

Slump Test

- Best known and most commonly used
  - https://www.youtube.com/watch?v=IwZf217v5XA
- Not suitable for concrete of very low and very high workability
  - For concrete with very low workability (zero slump), use Vebe time test
  - If the specimen "shear" or "collapse", repeat the test
  - For concrete with very high workability (collapse), consider Flow-Table test
- A report is required to state what form of slump is obtained and the slump value
- The test is sensitive to variations in operator technique







harsh, low on fines

plastic, cohesive

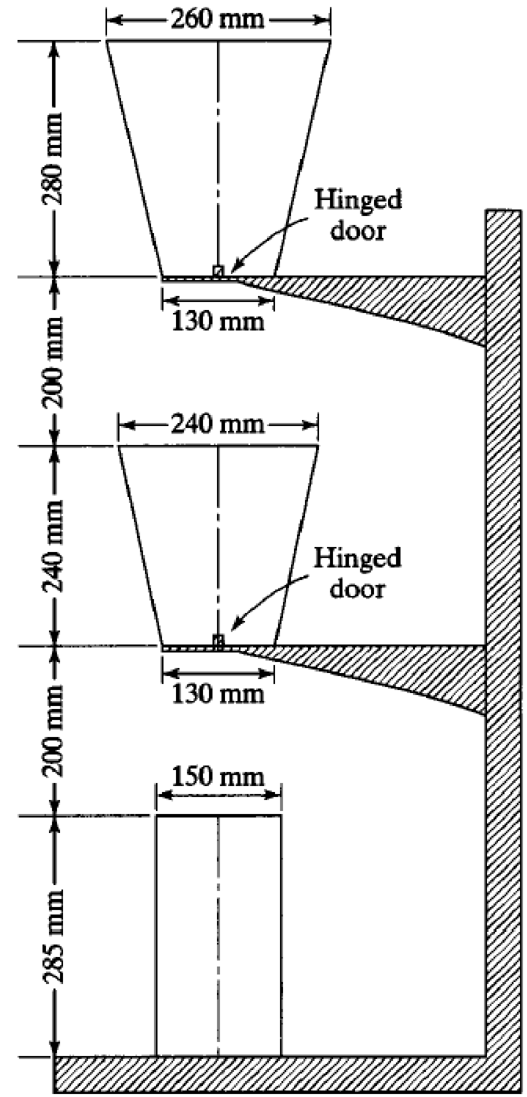
Gently tap concrete on the side to provide additional information on workability

Compaction Test

- Measure the degree of compaction produced by a given amount of work
  - Standard quantity of work is provided by allowing the concrete to fall under gravity through a standard distance
- Compacting factor = M_c / M_0

  M_c – Mass of partially compacted concrete

  M_0 – Mass of concrete required to fill the cylinder in full compaction (by manually Roding or using vibration table or internal vibrator)
- Disadvantages
  - Not suitable for field work
  - Some concrete tend to stick to the side of hopper



Flow Test

- For concrete of very high workability

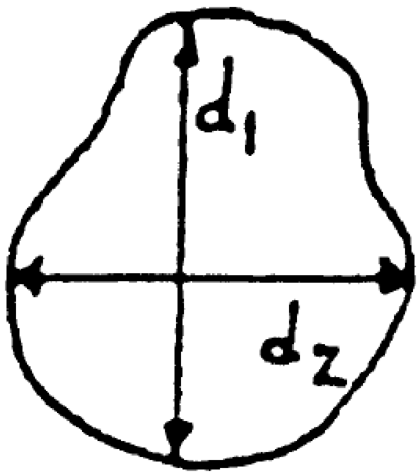
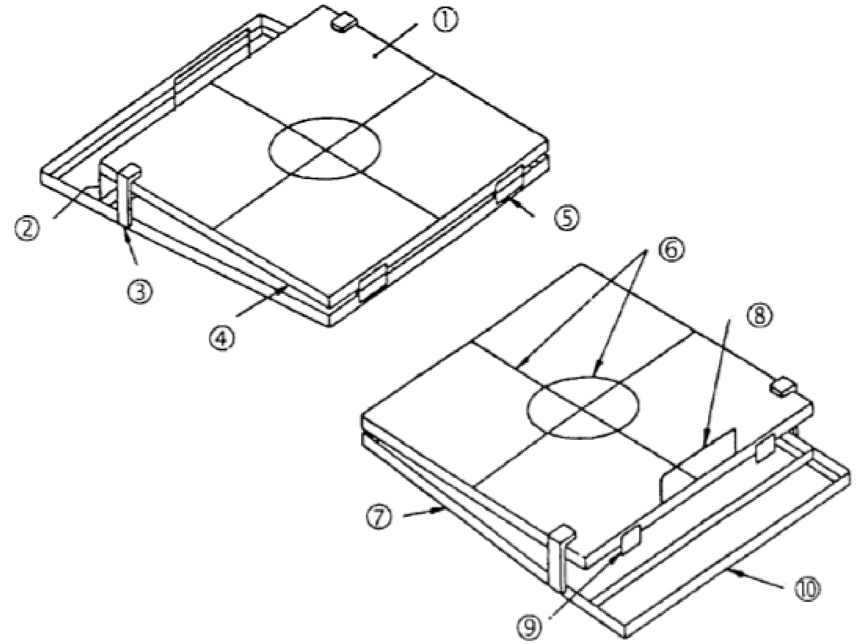


Figure 4 — Measurement of spread



Key

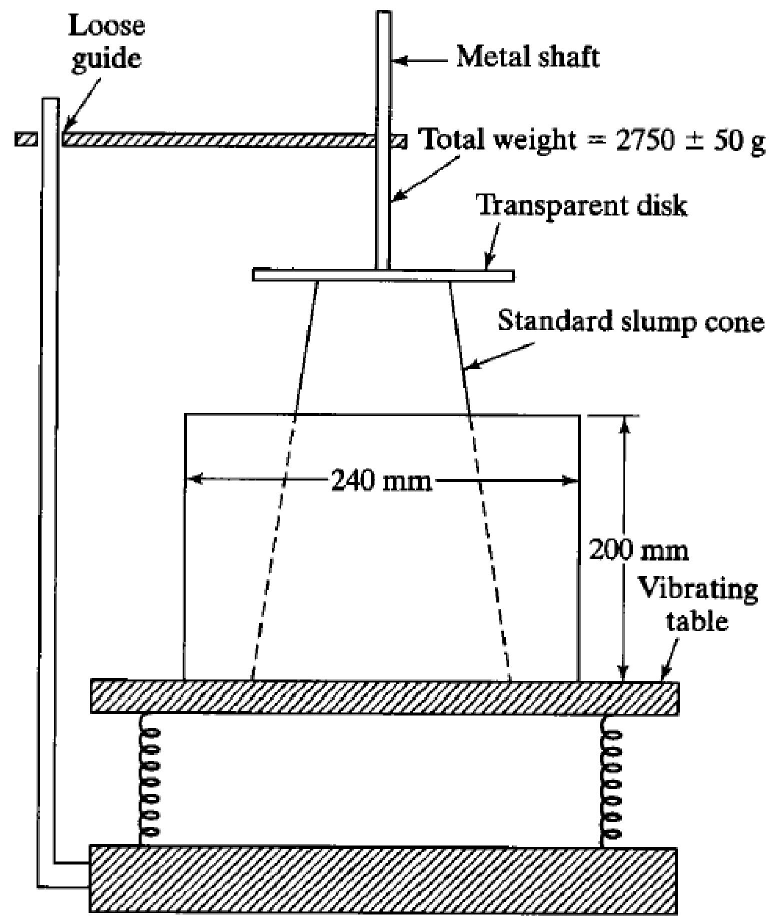
1) Metal plate
2) Travel limited to 40 ± 1
3) Upper stop
4) Table top
5) External hinges
6) Markings
7) Base frame
8) Lifing handle
9) Lower stop
10) Toe board

Figure 1 — Typical flow table

- "Spread" is used to evaluate the workability of concrete
  - taken as the arithmetic mean of the two diameters parallel to the sides of the table after 15 times of the fall of the upper board
- Resistance to segregation can be assessed qualitatively
  - In concrete mixes that are susceptible to segregation, the paste will tend to separate from the coarse aggregate around the perimeter of the concrete mass.

Remolding Test

- Measure the work required to cause concrete not only to flow, but also conform to a new shape
- Vebe Time
  - Defined as time required when the transparent disc is completely coated on its underside with cement paste
  - Reported as the Vebe seconds
  - The test is most suitable for concrete with VB from 5 to 30 s
  - Commonly used for
    - concrete with very low workability
    - fiber- reinforced concrete



Dscn0252.mov

Fresh concrete classes (SS EN 206-1)

Table 3 — Slump classes

Class	Slump in mm
S1	10 to 40
S2	50 to 90
S3	100 to 150
S4	160 to 210
S5[1)]	≥ 220

Table 4 — Vebe classes

Class	Vebe time in seconds
V0[1)]	≥ 31
V1	30 to 21
V2	20 to 11
V3	10 to 6
V4[1)]	5 to 3

Table 6 — Flow classes

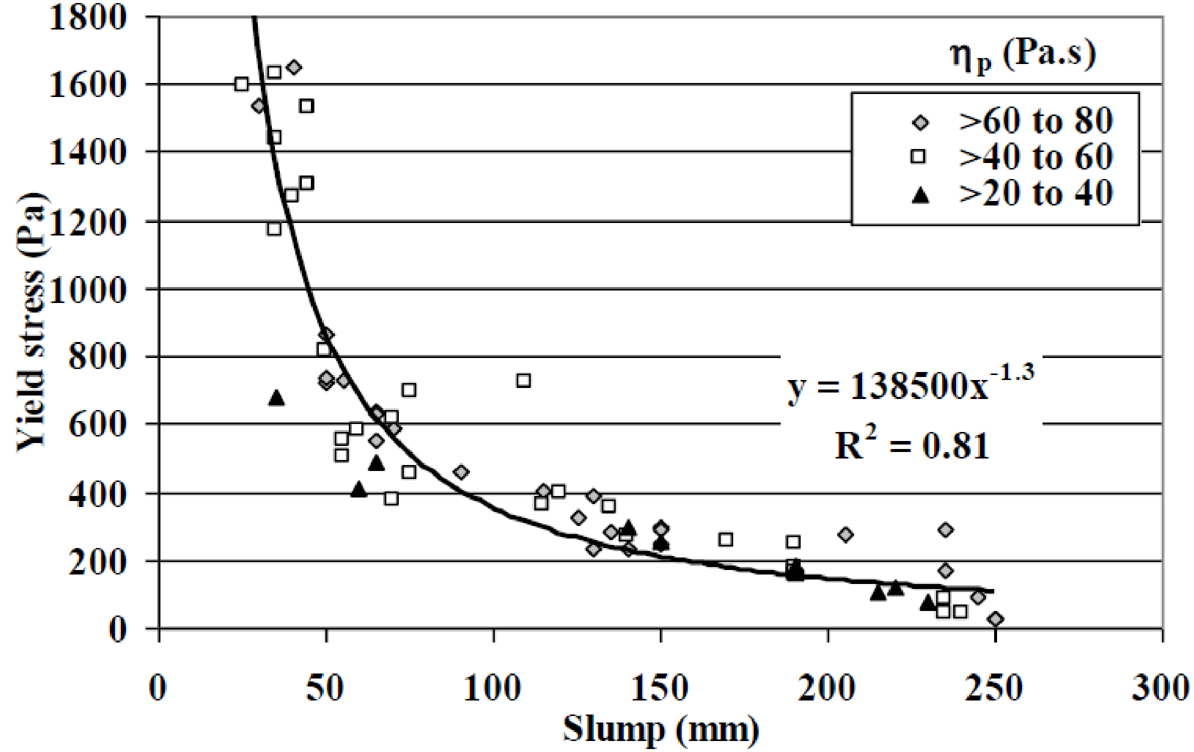
Class	Flow diameter in mm
F1[1)]	≤ 340
F2	350 to 410
F3	420 to 480
F4	490 to 550
F5	560 to 620
F6[1)]	≥ 630

1) Due to the lack of sensitivity of the test methods beyond certain values of consistence, it is recommended to use the indicated tests for:

- Slump: ≥ 10 mm & ≤ 210 mm
- Vebe time: ≤ 30 sec & > 3 sec
- Flow diameter: ≥ 340 mm & ≤ 620 mm

Relation between Slump and Rheological Parameters

Yield stress τ_o ↓, slump ↑



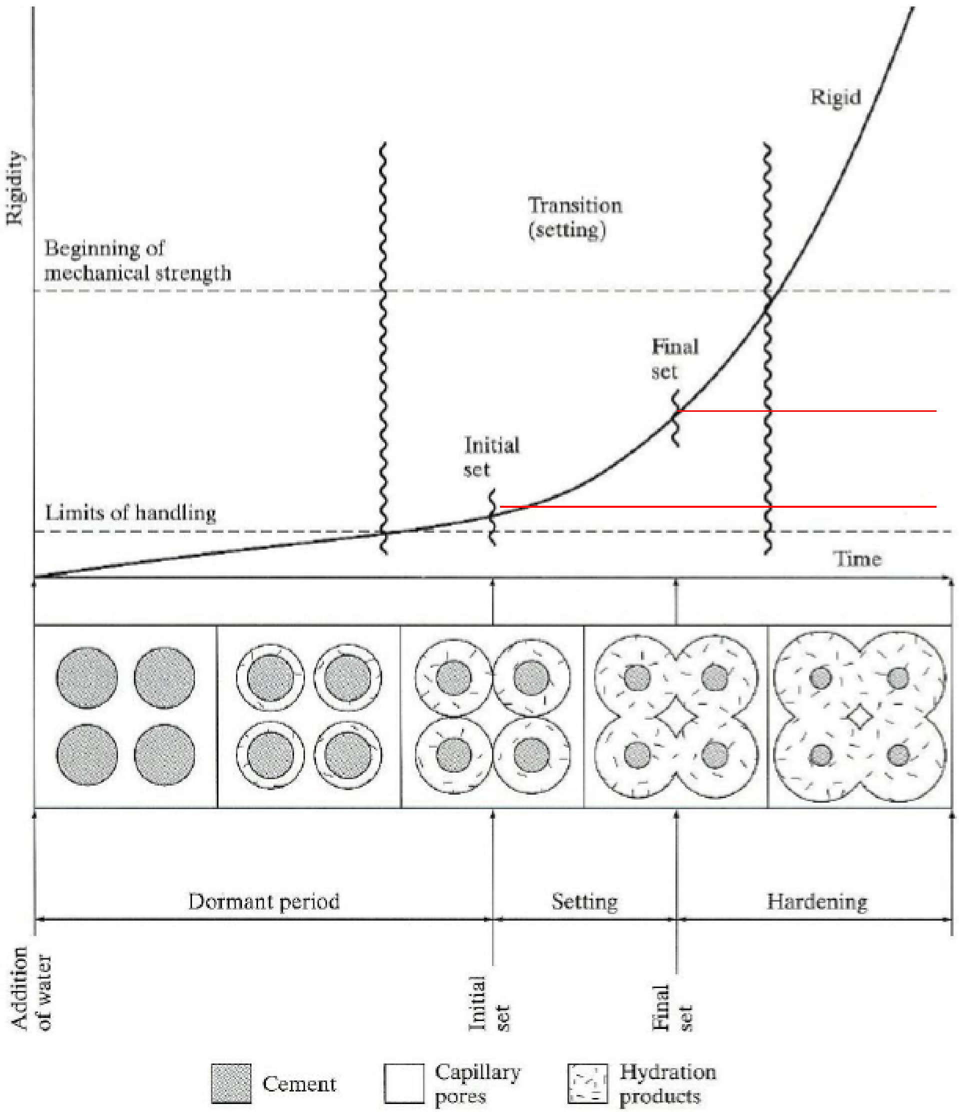
(Chia 2006)

- No clear correlation between plastic viscosity η_p and slump for non-air-entrained concrete
- For air-entrained concrete, air content ↑, plastic viscosity ↓, slump ↑

Setting of Concrete

- Defined as the onset of solidification in fresh concrete
- Transitional period between states of fluidity and rigidity
- Initial and final setting times of concrete are arbitrarily defined by a test method such as ASTM C 403 (penetration resistance method)
  - Do not mark a specific change in the physical-chemical characteristics of the cement paste or concrete; they are functional points
    - initial set: fresh concrete can no longer be properly handled and placed
    - final set: hardening begins
  - Used
    - to help regulate time of mixing and transportation
    - to help plan the scheduling of finishing operations
    - to determine the effectiveness of set-controlling admixtures

Setting and hardening



ASTM test

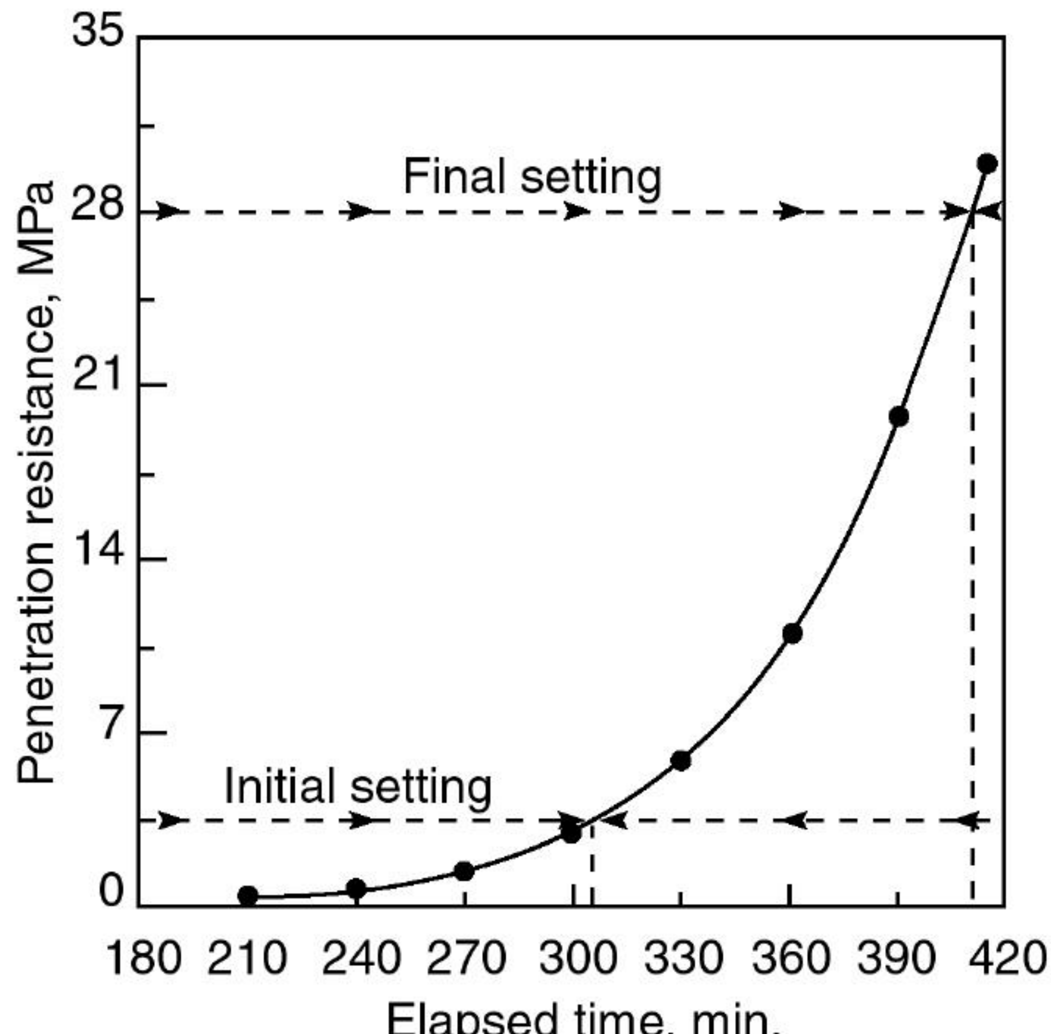
27.6 MPa

3.5 MPa

- **Setting**
  - When sufficient contact has formed between hydration products, paste lose its fluidity
- **Hardening**
  - Continued cement hydration leads to strength development

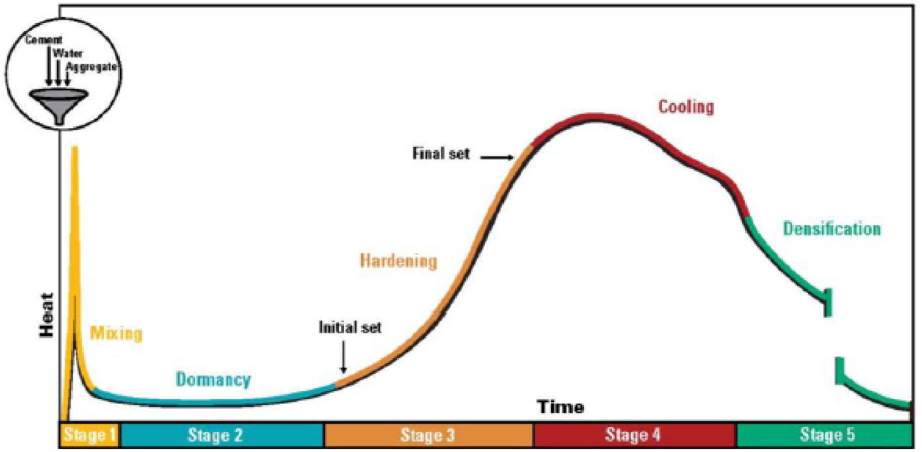
(Mindess &Young 1981) & (Soroka 1993)

Time of Setting — ASTM C 403



Effect of Hydration on Setting Time

- **Role of C_3S**
  - Setting is controlled primarily by the hydration of C_3S
  - Setting occurs when the induction period is terminated and rapid hydration of C_3S occurs in Stage 3
    - Initial set – beginning of Stage 3, beginning of rapid temperature rise
    - Final set – midpoint of Stage 3,
- **Role of C_3A & gypsum**
  - In OPC, C_3A plays a minor role in setting, except in cases of abnormal set
- w/c (w/c ↑, setting time ↑)
- Temperature
- Admixtures



Abnormal Setting & Stiffening

- **Sulphate related**
  - Delicate balance between C_3A and sulphate in solution in the first 15 min. If the balance is not right, problems
  - Form of calcium sulphate In cement
    - Gypsum $CaSO_4.2H_2O$
    - Hemi-hydrate $CaSO_4.1/2\ H_2O$
    - Anhydrate $CaSO_4$
  - Hemi-hydrate dissolves faster than gypsum
  - Anhydrate dissolves slowly

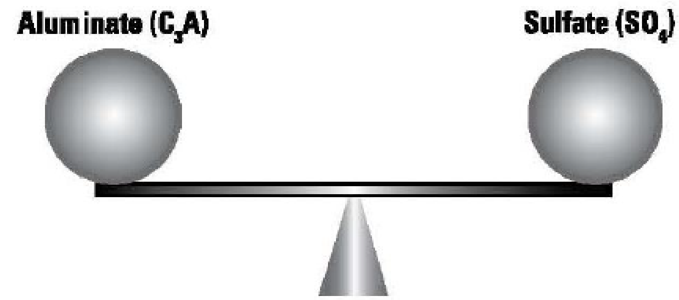
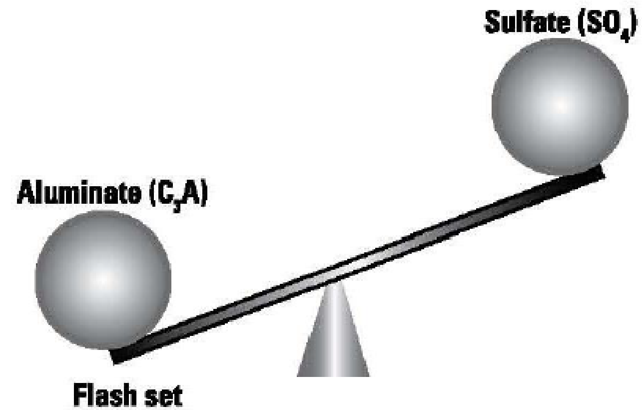


Figure 4-29. Early cement reactions are a balance of tricalcium aluminate (C_3A) and sulfate (SO_4) in solution. Excess of either will cause unexpected setting. (CTLGroup)

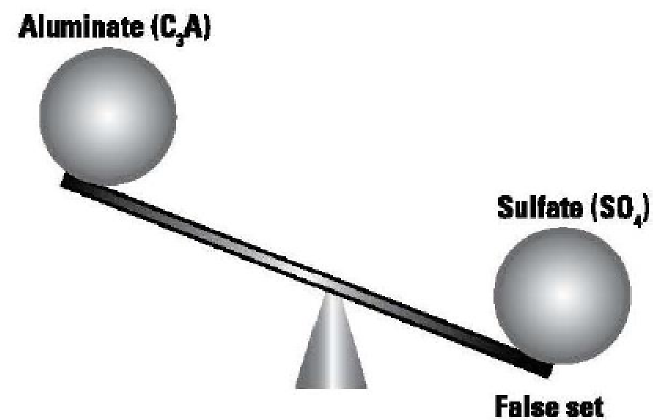
Rate of reaction: Hemihydrate > Gypsum > Anhydrate

Abnormal Setting & Stiffening

- **Flash set**
  - Insufficient sulphate in solution
  - C_3A reacts quickly with water to form CAH
  - Flash set: immediate and permanent hardening of mix



- **False set**
  - Too much sulphate in solution
  - Gypsum crystals precipitate
  - Causing temporary stiffening
  - If mixing continues, the gypsum will re-dissolve and the stiffening will disappear



(CTL Group)

Abnormal Setting Behavior

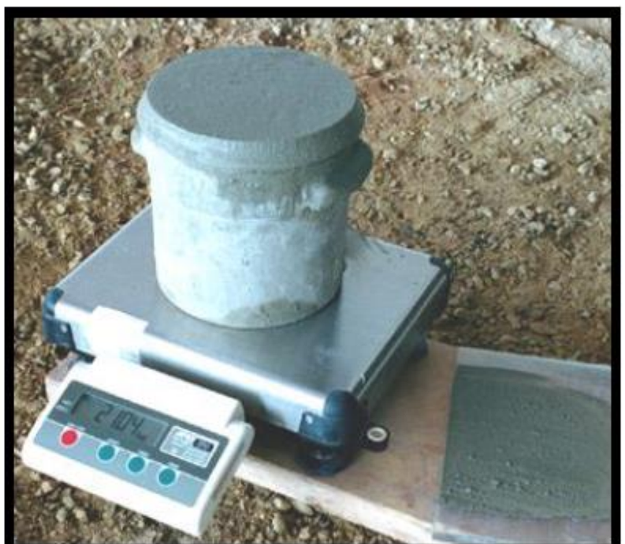
- **Water reducing admixtures related**
  - Some chemical admixtures (e.g. Type A or B) may interfere with cement hydration
    - Accelerate C_3A reaction
    - Retard C_3S reaction
  - Interfere with the balance of aluminate and sulphate
    - If the C_3A reaction is accelerated, $\rightarrow$ flash setting
  - Delay the addition of the WRAs
- **Supplementary cementing materials related**
  - An SCM containing high C_3A (typically Class C fly ash) can compromise the aluminate - sulphate balance
  - Flash setting
  - Desirable to use blended cements commercially produced instead of mixing cement and fly ash at ready mix concrete plants

Abnormal Setting Behavior

- Temperature related
  - High temperatures generally increase solubility (except CH) and accelerate the rate of cement hydration
  - Affect aluminate – sulphate balance
  - Consumption of gypsum in cement paste system occurs more quickly when the curing temperature is higher
  - In warm weather, more sulphate is needed to control rapid C_3A reactions

Tests of Fresh Concrete

- **As quality control measure and help to ensure proper mix proportions**
  - **Workability**
  - **Setting times**
  - **Air content**
  - **Unit weight**

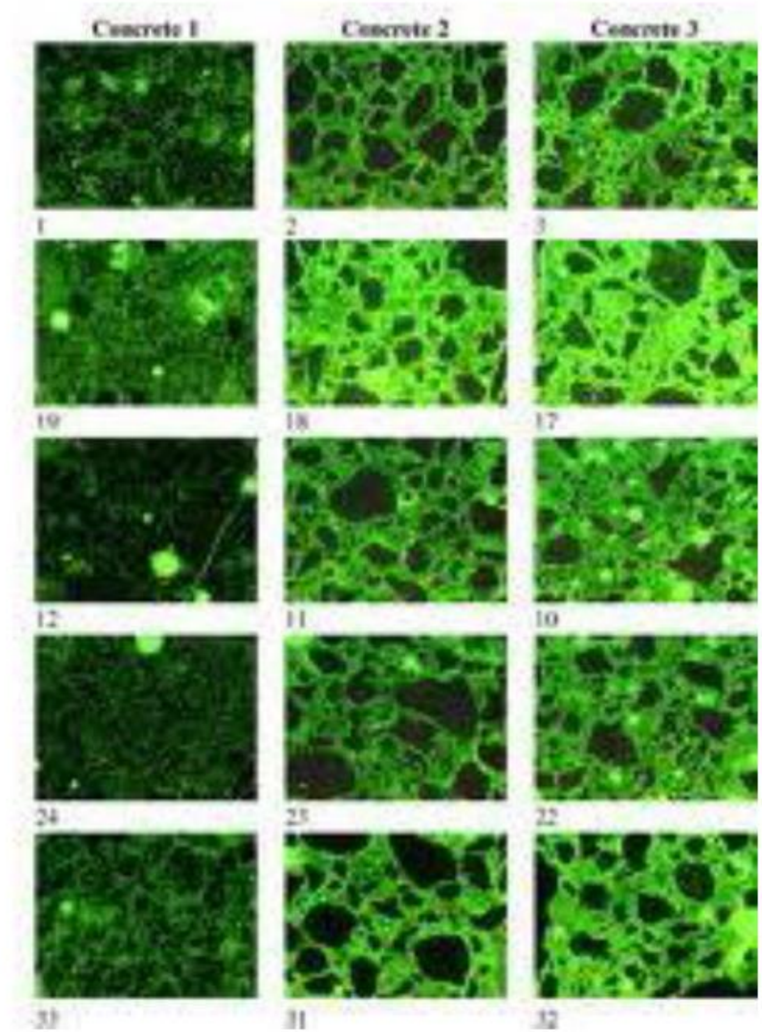


Unit weight

Air content

Quality Control of Concrete

- **Control**
  - Mix proportion
  - Compressive strength
  - Durability (if specified)
- **Importance of w/c and cement content**
  - No easy test method is available to determine w/c and cement content with sufficient accuracy
  - Determine w/c
    - Concrete thin section under optical microscope
    - Light intensity passed through the thin section $\propto$ w/c
    - Accuracy $\pm$ 0.05



(Jacobsen & Brown 2005)

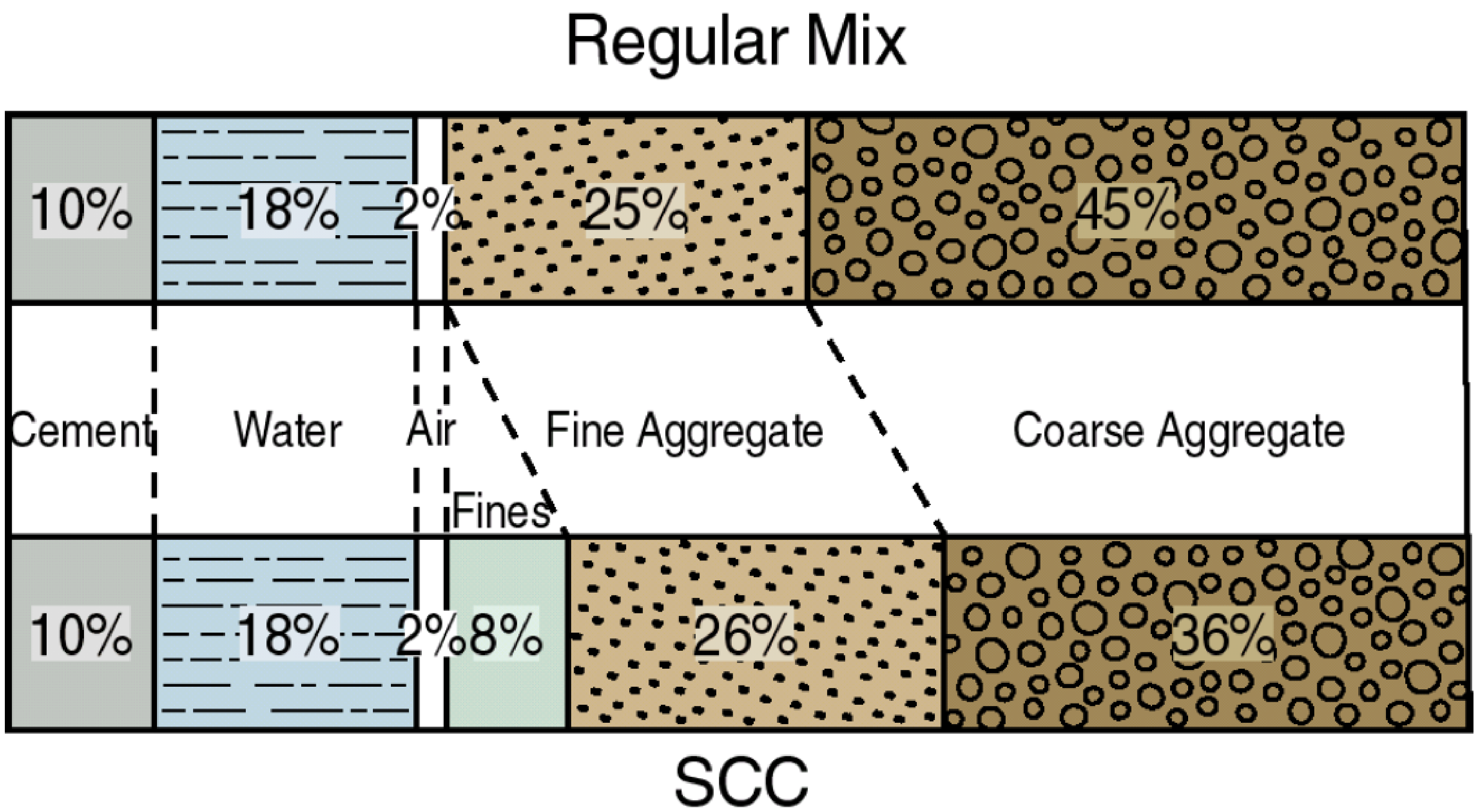
EN 12350 - Testing fresh concrete

- Part 1: Sampling
- Part 2: Slump test
- Part 3: Vebe test
- Part 4: Degree of compactability
- Part 5: Flow table test
- Part 6: Density
- Part 7: Air content: pressure methods

Self-Consolidating Concrete (SCC)

- **Self-Consolidating Concrete**
  - flowable concrete that consolidates around formwork without vibration or external energy
- **Self-leveling concrete**
  - does not need to be leveled during placement
- SCC is pumped and placed like ordinary concrete
- **Advantages**
  - Less equipment requirements
  - Less labor requirement at job site
  - Less surface defects

Self-Consolidating Concrete



Slump Flow Test



1. A traditional Abram's Cone (normal or inverted) is filled in one lift (no rodding or other consolidation) with SCC, taking care to be sure the sample is well mixed and not segregated in the sampling process.
2. The cone is then raised over 5 seconds to a height of 12 inches, allowing the fluid concrete to flow onto the slump flow board.
3. The slump flow is the diameter of the resulting concrete "patty" obtained from the average of measuring the greatest diameter and diameter perpendicular to this direction .
4. The result is reported to the nearest half inch.

ACI Spring 2005 Convention – E 802

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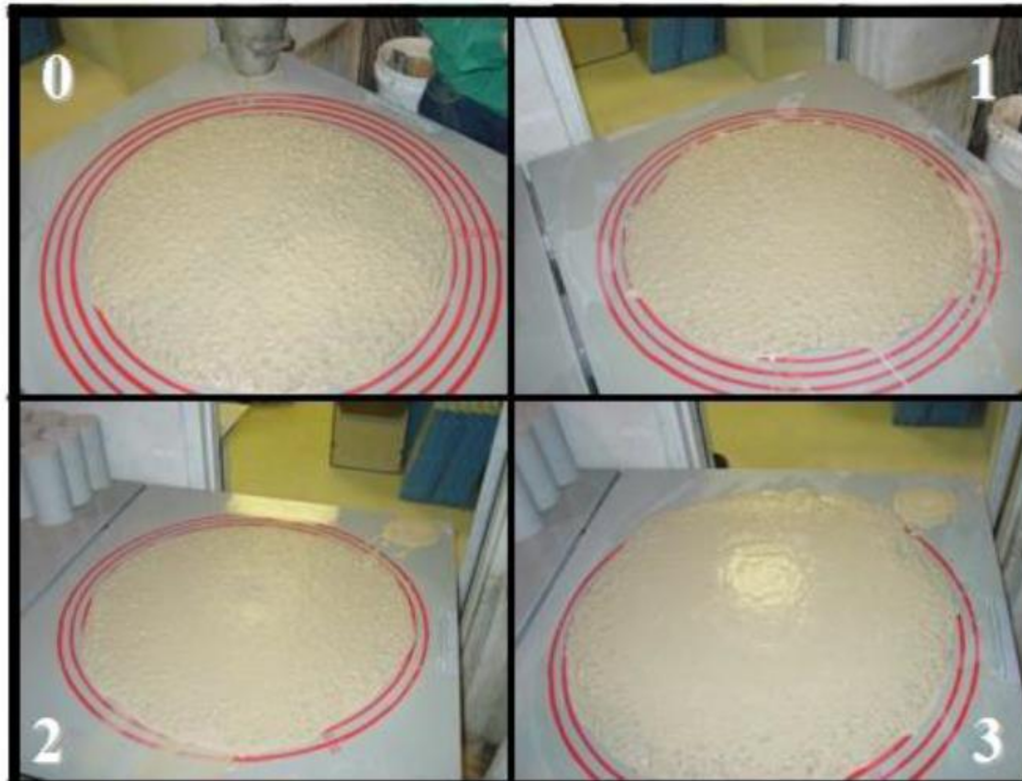
https://www.youtube.com/watch?v=QQyx7oy4P-g (EN 12350 Part 8)

Visual Stability Index (VSI)

1. The VSI test ranks the stability of the SCC on a scale of 0-3 with 0 indicating highly stable SCC and 3 indicating unacceptable SCC.

2. The rating is based on the visual inspection of the slump flow patty immediately after it stops flowing.

3. The appearance of the patty is then compared to pictures and descriptions of the surface bleed, mortar halo, and aggregate distribution.



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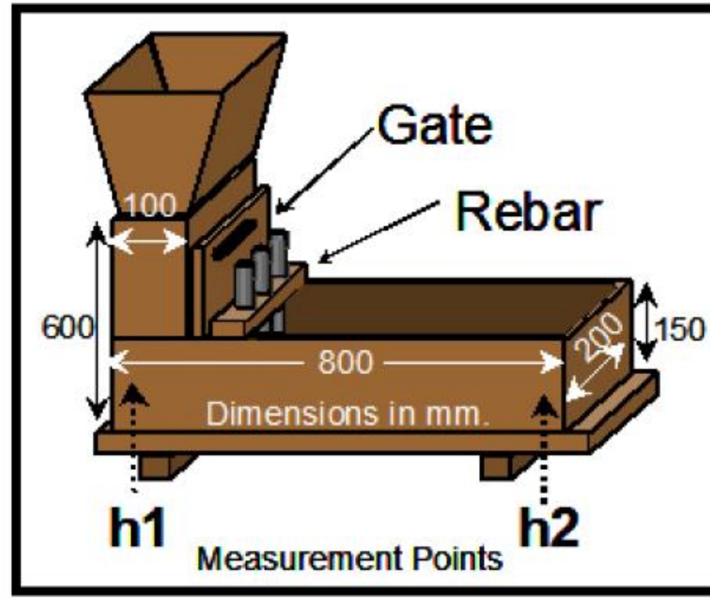
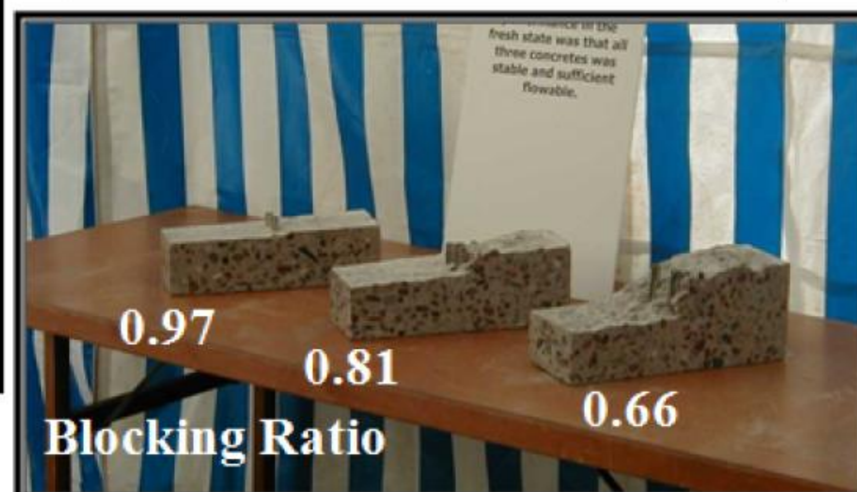
L-box Test

SCC Test Methods – *L-Box*

1. With the gate closed, the vertical column of the L-box is filled in one lift (no rodding or other consolidation).
2. The gate is lifted and the SCC flows through the rebar obstructions and into the horizontal portion of the L-box.
3. The filling ability is described by the ratio of the cement height at the end of the horizontal section (h2) to the height at the beginning of the horizontal section (h1).
4. Typically, h2/h1 is greater than 0.9.
5. Passing ability is indicated by visual inspection of the area around the rebar – with an even distribution of aggregate indicating good passing ability.





https://www.youtube.com/watch?v=LWaAFjZ-nwA
(EN 12350 Part 10)

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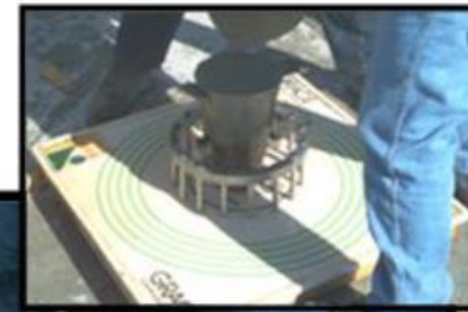
SCC Test Methods – *J-Ring*



1. This test is carried out in combination with the slump flow measurement as described above. The Abram's cone must be in the inverted orientation.
2. After the initial slump flow measurement (d1), the J-ring is placed in the center of the slump flow board. The inverted Abram's cone is placed inside the J-ring and is filled in one lift.
3. The cone is raised to a height of 12 inches over five seconds. The SCC flows through the reinforcing bars of the J-ring and onto the slump flow board.
4. The diameter of the slump flow patty is again measured to provide the "slump flow with J-ring", d2. The ratio of d2/d1 is an indication of the passing ability and is typically >0.9.
5. Visual inspection of the area around the rebar provides a qualitative indication of the passing ability, with an even distribution of aggregate around the rebar indicating good passing ability.

https://www.youtube.com/watch?v=iekYHyturZA (EN 12350 Part 12)

Properties of SCC in comparison to ordinary concrete

- Superior workability
  - achieved by a higher cement paste-to-aggregate ratio
- Higher drying shrinkage

Applications

- Heavily reinforced structures
- In North America
  - SCC is being used primarily in precast concrete plants
  - Ready mix concrete plants are reluctant to produce SCC (high cost, additional requirements for quality control)