Relationship between Rheology and Flowable Concrete Workability

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Things you Need to Know about Workability of Concrete - 2009 Fall Convention

First encounter with rheology

Rio.. what.. ?

Rheology affects ease of mixing, pumping, flow, segregation, washout, formwork pressure, surface finish, microstructure development ...

Oh, I see!

Rheology vs. slump and washout

<table>
<thead>
<tr>
<th>Binder</th>
<th>100% cement &amp; 8% silica fume</th>
</tr>
</thead>
<tbody>
<tr>
<td>W/CM</td>
<td>0.37 0.41 0.47 0.47</td>
</tr>
<tr>
<td>CM (kg/m(^3))</td>
<td>450 420 400 540</td>
</tr>
<tr>
<td>Sand / agg.</td>
<td>0.41 0.41 0.41 0.47</td>
</tr>
<tr>
<td>Slump (mm)</td>
<td>220 190 220 270 SCC UWC</td>
</tr>
</tbody>
</table>

Welan gum (% cwt) | 0, 0.05, 0.10, and 0.15

Cell. (mL/100 kg CM) | 600, 900, and 1200

Khayat and Assaad, 2003

Rheology of Underwater Concrete

Washout loss test (CRD C61)

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Relationship between Rheology and Flowable Concrete Workability
Washout not a function of slump

Effect AWA + HRWRA on g and h

Workability box for washout loss
Relationship between Rheology and Flowable Concrete Workability

- Rheology vs. washout resistance
- Rheology vs. workability of SCC
  - Rheology vs. workability test methods
  - Workability of fiber-reinforced SCC
  - Effect of mix design on rheology of SCC
- Rheology vs. hardening properties
  - Form pressure
  - Interlayer bond of green SCC
  - Top-bar effect

Flow behavior of SCC is complex and must be optimized to secure adequate performance.

- Low resistance to flow (low $\tau_0$)
- High stability (moderate visc.)
- High passing ability (low $\tau_0$ + moderate visc.)

Rheology of matrix must be controlled to avoid particle segregation.

- Low yield value and viscosity
- Lack of static stability after casting

\[ \tau_y \geq \frac{2}{3} g (\rho_p - \rho_m) MSA \]

Laboratory & field test methods to assess SCC workability.

T50 vs. h

- Cement content = 385 kg/m³
- Cement content = 500 kg/m³

V-funnel flow vs. h

- Cement content = 385 kg/m³
- Cement content = 500 kg/m³

Khayat et al. 2004
**Relationship between Rheology and Flowable Concrete Workability**

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**Increase of L-box and U-box flow times with h**

- L-box test; $R^2 = 0.65$
- U-box test; $R^2 = 0.74$

Khayat et al. 2004

**Correlate workability characteristics to intrinsic rheological properties**

- U-box test
- $R^2 = 0.74$

Khayat et al. 2004

**Viscosity vs. passing ability**

- $N = 24$
- $R^2 = 0.81$

NCHRP 628, 2005

**Viscosity vs. static stability**

- $\tau_s \geq 2/3\left(\rho_g - \rho_m\right)MSA$

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**Surface settlement**

- $\phi = 670 \pm 20\text{ mm}$

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**Surface settlement vs. $\mu_p$**

NCHRP 628, 2005
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Variations in lateral pressure envelope

Loss in slump flow is not sufficient to evaluate decay in lateral pressure

Filling capacity of FR-SCC can be related to rheological parameters

Khayat and Roussel, 2000

Khayat and Roussel, 2000

Khayat et al., 2003
**Thixotropy:** variation of viscosity with time at constant shear rate (reversible)

![Graph showing thixotropy](image)

**Testing protocol of thixotropy**

![Graph showing testing protocol](image)

**A_b** vs. lateral pressure measured initially and after 100 and 200 min

![Graph showing A_b vs. lateral pressure](image)

**Field validation**

H = 5.5 - 6 m  
L = 7 m  
W = 0.19 m  
As = 0.4%

**Typical formwork pressure diagram**

![Graph showing formwork pressure](image)

**Actual pressure is less than hydrostatic!**

![Graph showing actual pressure](image)
**Relationship between Rheology and Flowable Concrete Workability**

- **Structural build-up: Static yield stress at rest**
  \[ T_{\text{rest}} = T_{\text{max}}/G \]
  - \( T_{\text{max}} \): Torque at maximum
  - \( G \): Shear modulus
  - \( N = 0.03 \text{ rps} \)

- **Homogeneity of bond strength**
  - \( H = 1.5 \text{ m} \)
  - SCC mixtures:
    - J-Ring: 630 – 640 mm
    - L-box ≥ 0.75
    - Filling capacity ≥ 90%
    - VSI: 0 – 1

- **In-situ compressive strength**
  - \( f'_{c} \): Core/Bottom compressive strength
  - Dist. from bottom (cm):
    - 0
    - 30
    - 60
    - 90
    - 120
    - 150
  - High \( \mu_{p}, A_{b} \)
  - Med. \( \mu_{p}, A_{b} \)
  - Low \( \tau_{0}, \mu_{p}, A_{b} \)

- **Top-bar effect**
  - Dist. from bottom (cm):
    - 0.8
    - 1.0
    - 1.2
    - 1.4
    - 1.6
    - 1.8
    - 2.0
  - \( f'_{c} \): Core/Bottom/In-situ compressive strength
  - \( f'_{c} = f'_{c} \text{ (bottom)} \)
  - \( f'_{c} = f'_{c} \text{ (in-situ)} \)
  - \( U'/U'_{\text{bottom}} \)
  - \( U'/U'_{\text{in-situ}} \)

- **Surface settlement (%)**
  - Blapsed time (hour):
    - 0
    - 2
    - 4
    - 6
    - 8
  - Med. \( \mu_{p}, A_{b} \)
  - Low \( \mu_{p}, A_{b} \)
  - Vibrated HPC

- **K\(_{0}\) = f(H, R, D\(_{\text{min}}\), \tau_{0\text{rest}}, PV_{\tau_{0\text{rest}}}, MSA, WP)\**
  - \( H = 2 \text{ m} \)
  - \( R = 2 \text{ ml/hr} \)
  - \( T = 22 \text{ °C} \)
  - \( D_{\text{min}} = 200 \text{ mm} \)
  - MSA = 14 mm
  - WP ≥ 0
  - \( \tau_{0\text{rest}} = T_{\text{max}}/G \)
  - \( PV_{\tau_{0\text{rest}}} \)

- **Lack of proper consolidation**

- **In-situ compressive strength**
  - Core/Bottom compressive strength

- **Top-bar effect**
  - In-situ versus bottom compressive strength
### Recommended values to ensure homogeneous properties

<table>
<thead>
<tr>
<th>Static stability</th>
<th>Maximum surface settlement $\leq 0.5%$</th>
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<tbody>
<tr>
<td></td>
<td>Column segregation index ($I_{seg}$) $\leq 5%$</td>
</tr>
<tr>
<td></td>
<td>Percent static segregation ($S$) $\leq 15$</td>
</tr>
<tr>
<td>Viscosity</td>
<td>Plastic viscosity $\leq 0.073$ psi.s (500 Pa.s)</td>
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<td></td>
<td>(Modified Tattersall two-point rheometer with vane device)</td>
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<tr>
<td>Mechanical properties</td>
<td>Core-to-cylinder compressive strength $\geq 90%$</td>
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<tr>
<td></td>
<td>(similar curing conditions)</td>
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<tr>
<td></td>
<td>Bond strength modification factor $\leq 1.4$</td>
</tr>
</tbody>
</table>

NCHRP 628, 2009

### References