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Relationship between Rheology and Flowable Concrete Workability

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

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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

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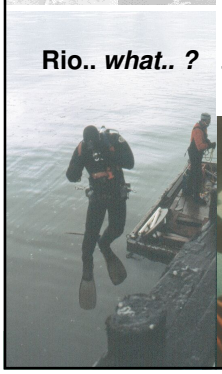
First encounter with rheology



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

Rheology vs. slump and washout

Binder	100% cement & 8% silica fume			
W/CM	0.37	0.41	0.47	0.47
CM (kg/m^3)	450	420	400	540
Sand / agg.	0.41	0.41	0.41	0.47
Slump (mm)	220	190	220	270 SCC UWC

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

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

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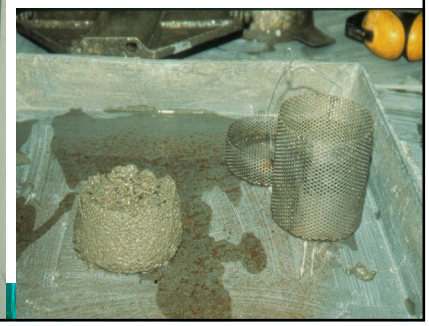
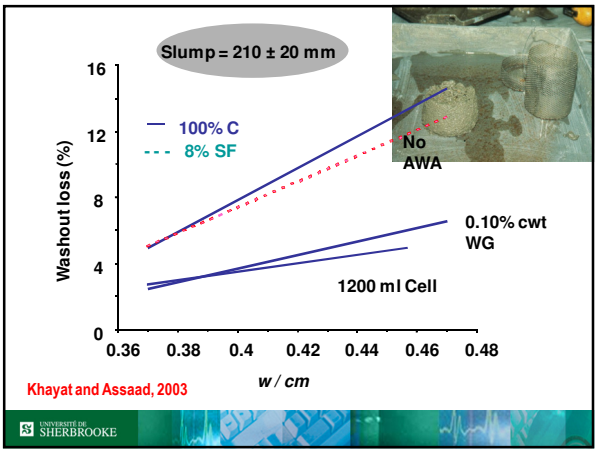
Rheology of Underwater Concrete

Washout loss test (CRD C61)





Khayat and Assaad, 2003

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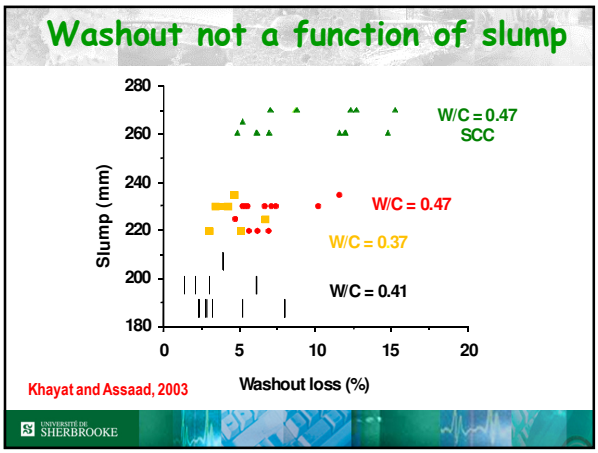
Washout not a function of slump
Slump (mm)
Washout loss (%)
W/C = 0.47
SCC
W/C = 0.47
W/C = 0.37
W/C = 0.41
Khayat and Assaad, 2003
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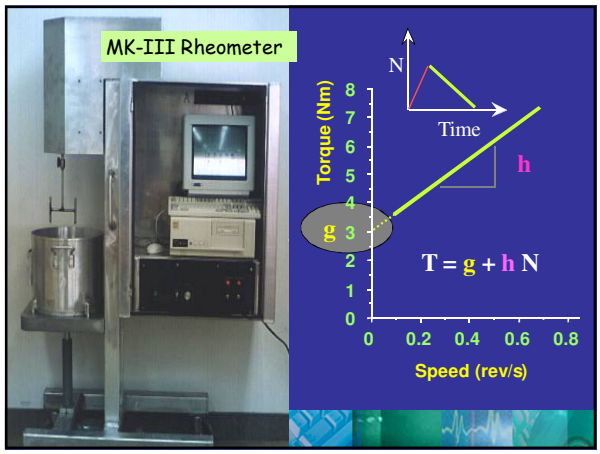
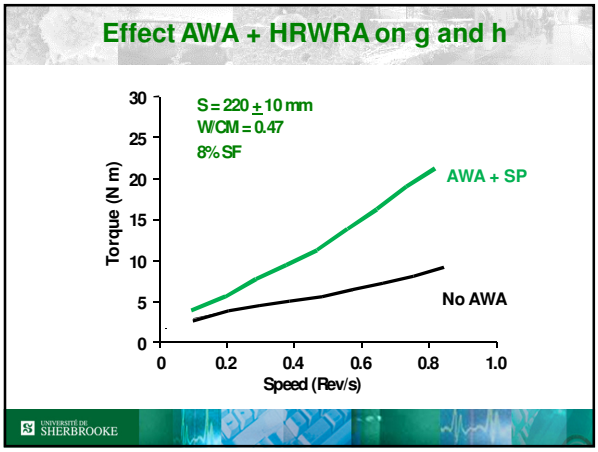

MK-III Rheometer
Torque (Nm)
Speed (rev/s)
N
Time
h
g
T = g + h N


Effect AWA + HRWRA on g and h
S = 220 ± 10 mm
W/CM = 0.47
8% SF
AWA + SP
No AWA
Torque (N m)
Speed (Rev/s)
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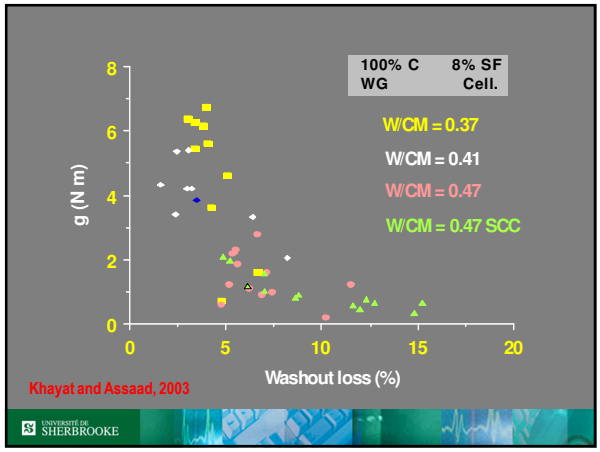
100% C 8% SF
WG Cell.
W/CM = 0.37
W/CM = 0.41
W/CM = 0.47
W/CM = 0.47 SCC
g (N m)
Washout loss (%)
Khayat and Assaad, 2003
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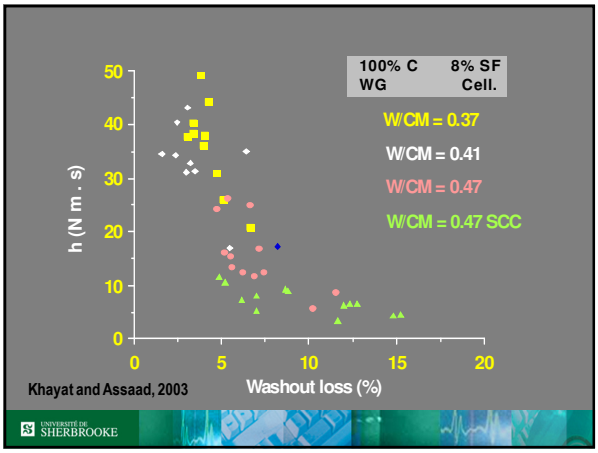
100% C 8% SF
WG Cell.
W/CM = 0.37
W/CM = 0.41
W/CM = 0.47
W/CM = 0.47 SCC
h (N m . s)
Washout loss (%)
Khayat and Assaad, 2003
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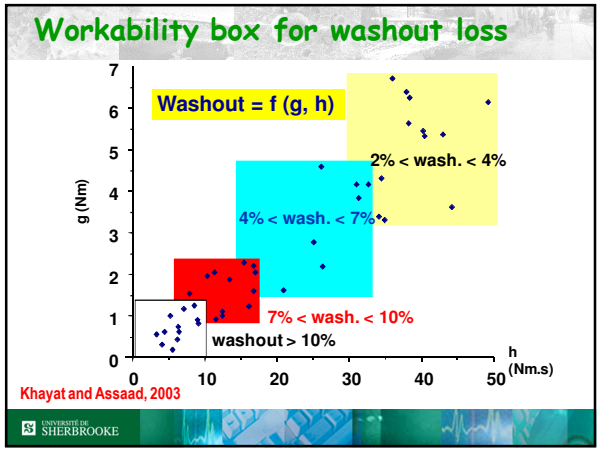
Workability box for washout loss
Washout = f (g, h)
2% < wash. < 4%
4% < wash. < 7%
7% < wash. < 10%
washout > 10%
g (Nm)
h (Nm.s)
Khayat and Assaad, 2003
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Relationship between Rheology and Flowable Concrete Workability

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

low resistance to flow (low τ_0)

high stability (moderate visc.)

high passing ability (low τ_0 + mod. visc.)

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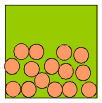
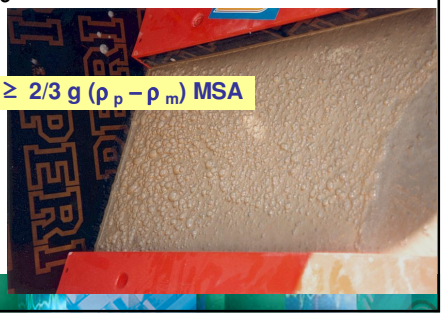
Rheology of matrix must be controlled to avoid particle segregation

Lack of static stability after casting

low yield value and viscosity

$\tau_y \geq 2/3\ g\ (\rho_p - \rho_m)$ MSA





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Laboratory & field test methods to assess SCC workability

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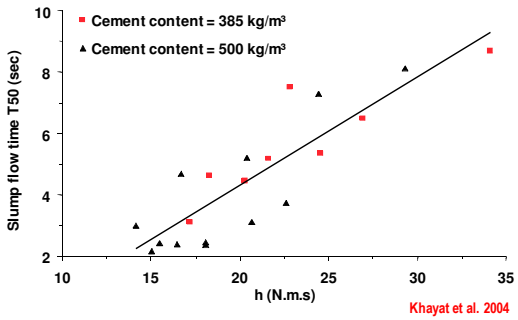
T50 vs. h



Khayat et al. 2004

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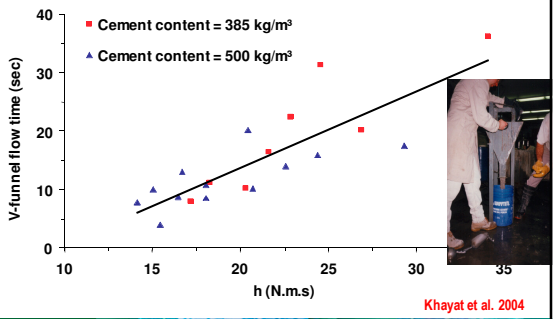
V-funnel flow vs. h



Khayat et al. 2004

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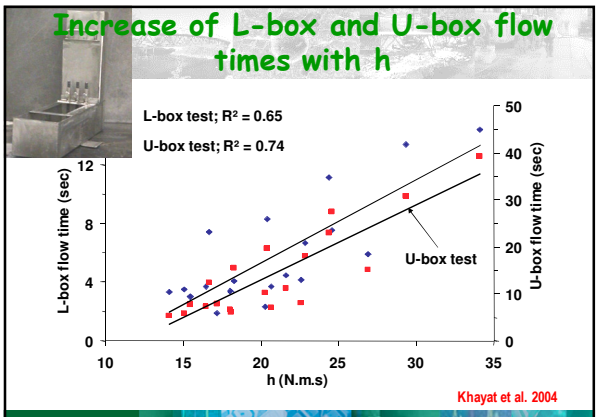
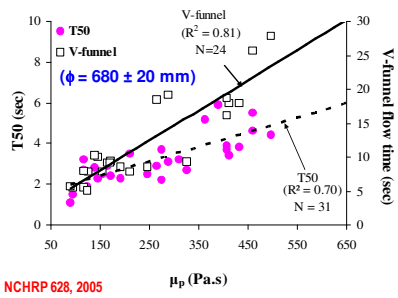
Increase of L-box and U-box flow times with h



Khayat et al. 2004

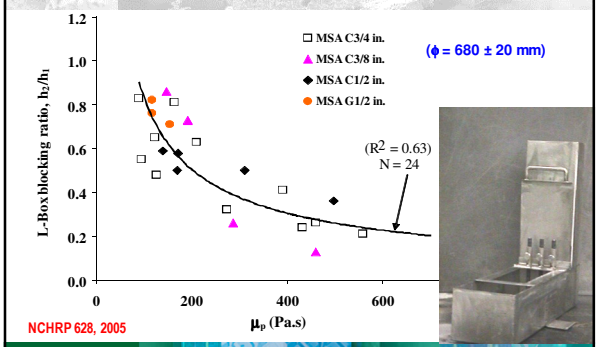
Correlate workability characteristics to intrinsic rheological properties



	Relative error, %
T50	27
V-funnel	34
μ_p	8

NCHRP 628, 2005

Viscosity vs. passing ability



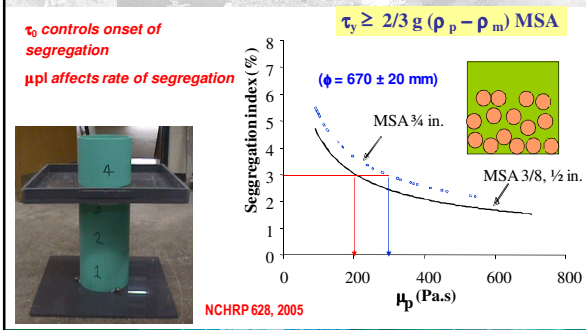
NCHRP 628, 2005

Viscosity vs. static stability

$\tau_y \geq 2/3\, g\, (\rho_p - \rho_m)$ MSA

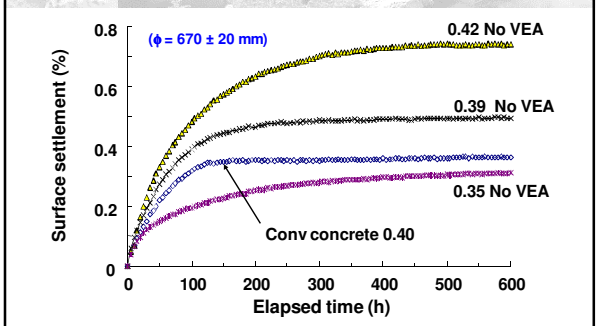
τ_0 controls onset of segregation

μpl affects rate of segregation

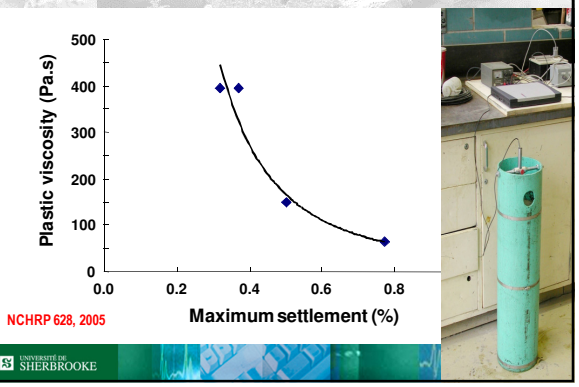


NCHRP 628, 2005

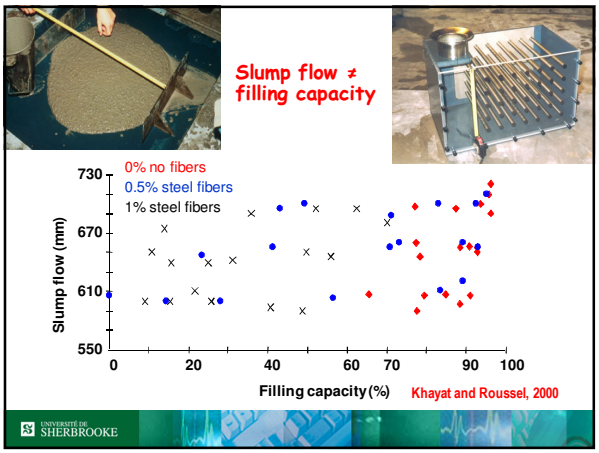
Surface settlement



Surface settlement vs. μp



NCHRP 628, 2005


Slump flow ≠ filling capacity
0% no fibers
0.5% steel fibers
1% steel fibers
Slump flow (mm)
730
670
610
550
0
20
40
60
70
90
100
Filling capacity (%)
Khayat and Roussel, 2000
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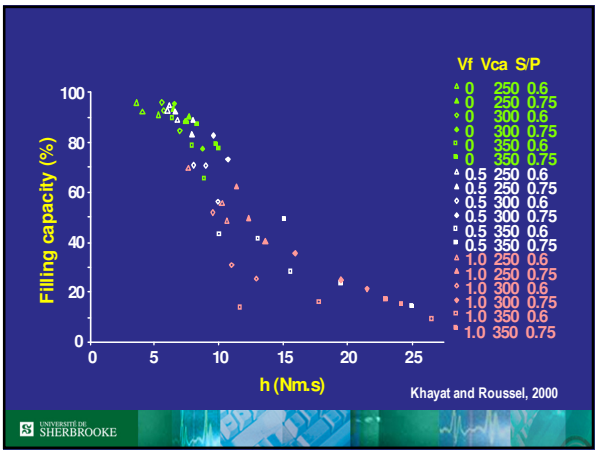
Vf Vca S/P
0 250 0.6
0 250 0.75
0 300 0.6
0 300 0.75
0 350 0.6
0 350 0.75
0.5 250 0.6
0.5 250 0.75
0.5 300 0.6
0.5 300 0.75
0.5 350 0.6
0.5 350 0.75
1.0 250 0.6
1.0 250 0.75
1.0 300 0.6
1.0 300 0.75
1.0 350 0.6
1.0 350 0.75
Filling capacity (%)
100
80
60
40
20
0
0
5
10
15
20
25
h (Nm.s)
Khayat and Roussel, 2000
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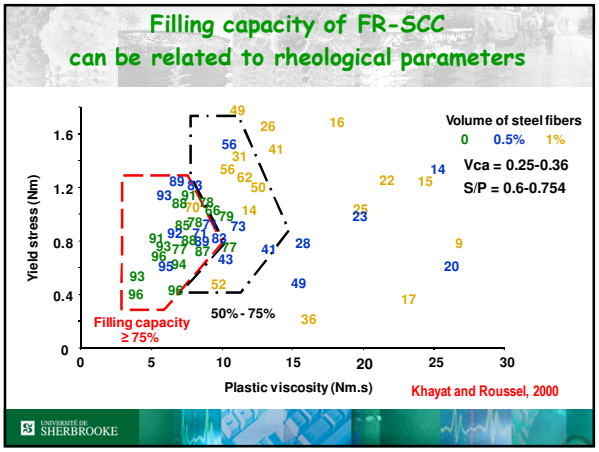
Filling capacity of FR-SCC can be related to rheological parameters
Volume of steel fibers
0 0.5% 1%
Vca = 0.25-0.36
S/P = 0.6-0.754
Yield stress (Nm)
1.6
1.2
0.8
0.4
0
0
5
10
15
20
25
30
Plastic viscosity (Nm.s)
Filling capacity ≥ 75%
50%- 75%
Khayat and Roussel, 2000
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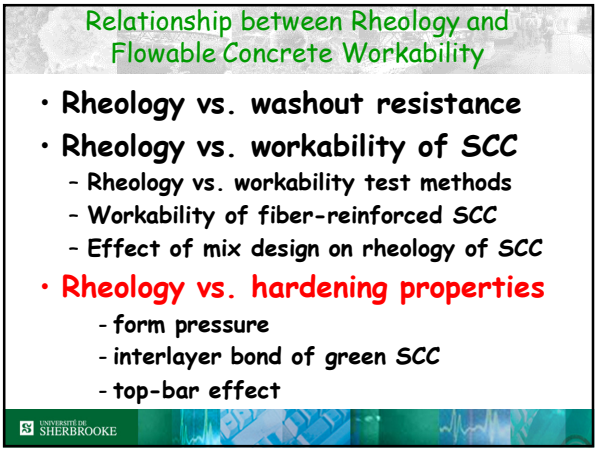
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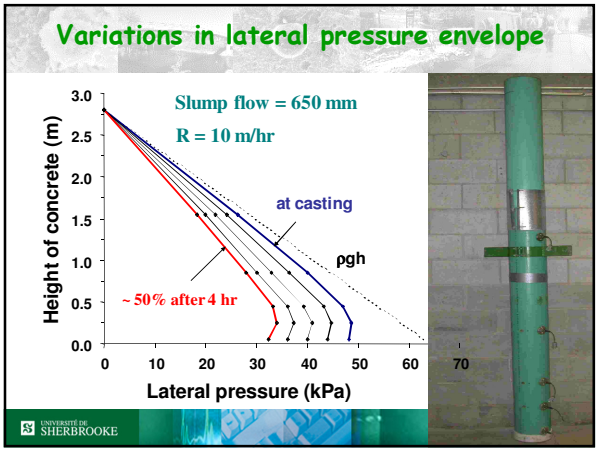
Variations in lateral pressure envelope
Slump flow = 650 mm
R = 10 m/hr
at casting
ρgh
~ 50% after 4 hr
Height of concrete (m)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
10
20
30
40
50
60
70
Lateral pressure (kPa)
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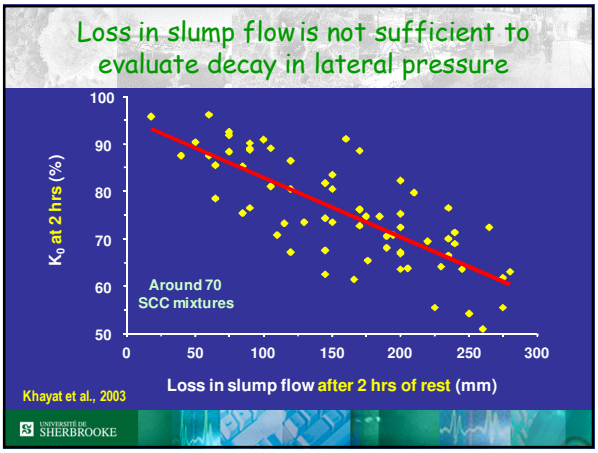
Loss in slump flow is not sufficient to evaluate decay in lateral pressure
K0 at 2 hrs (%)
100
90
80
70
60
50
Around 70 SCC mixtures
0
50
100
150
200
250
300
Loss in slump flow after 2 hrs of rest (mm)
Khayat et al., 2003
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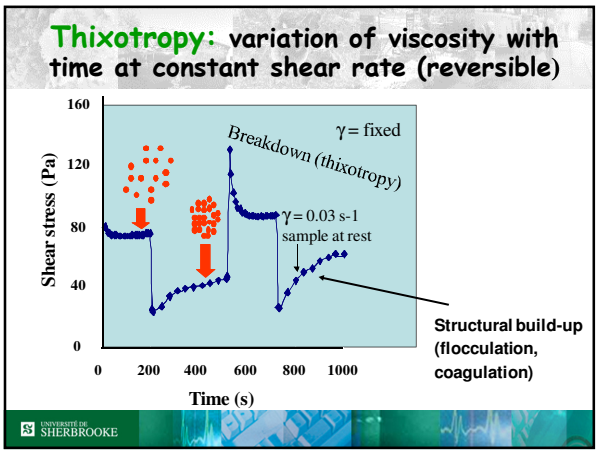
Thixotropy: variation of viscosity with time at constant shear rate (reversible)
Shear stress (Pa)
Time (s)
γ = fixed
Breakdown (thixotropy)
γ = 0.03 s-1
sample at rest
Structural build-up (flocculation, coagulation)
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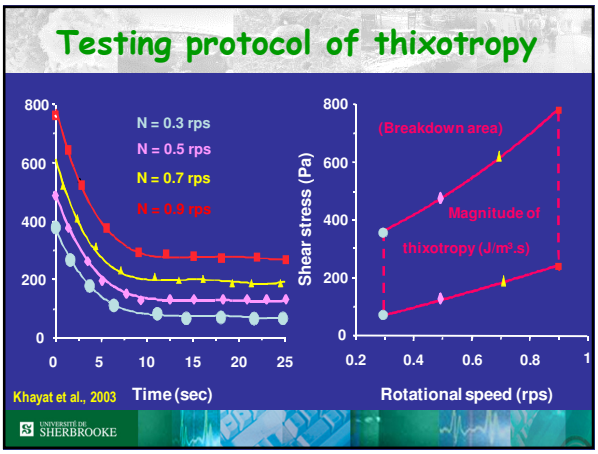
Testing protocol of thixotropy
N = 0.3 rps
N = 0.5 rps
N = 0.7 rps
N = 0.9 rps
Time (sec)
Shear stress (Pa)
(Breakdown area)
Magnitude of thixotropy (J/m³.s)
Rotational speed (rps)
Khayat et al., 2003
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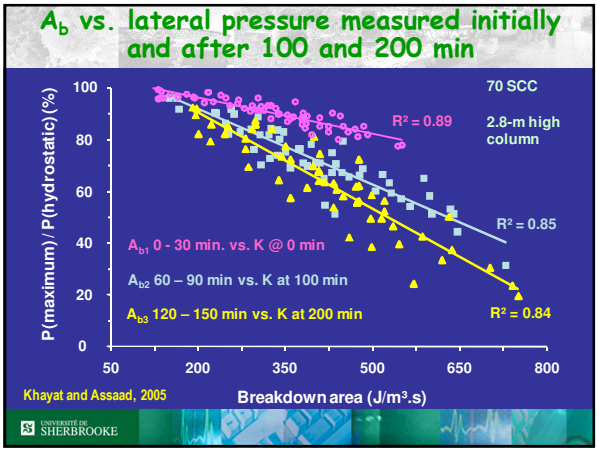
Ab vs. lateral pressure measured initially and after 100 and 200 min
P(maximum)/ P(hydrostatic) (%)
70 SCC
2.8-m high column
R² = 0.89
R² = 0.85
R² = 0.84
Ab1 0 - 30 min. vs. K @ 0 min
Ab2 60 – 90 min vs. K at 100 min
Ab3 120 – 150 min vs. K at 200 min
Breakdown area (J/m³.s)
Khayat and Assaad, 2005
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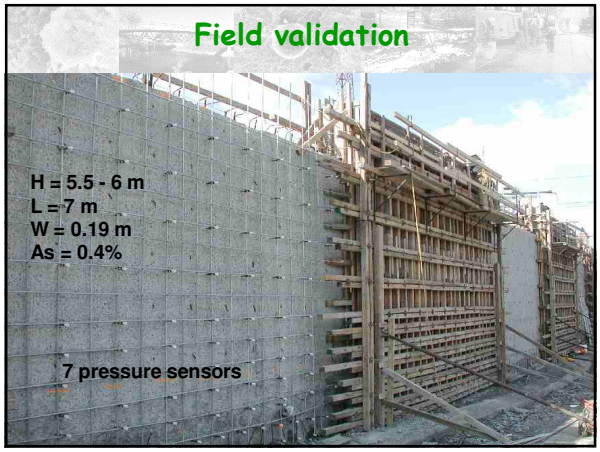
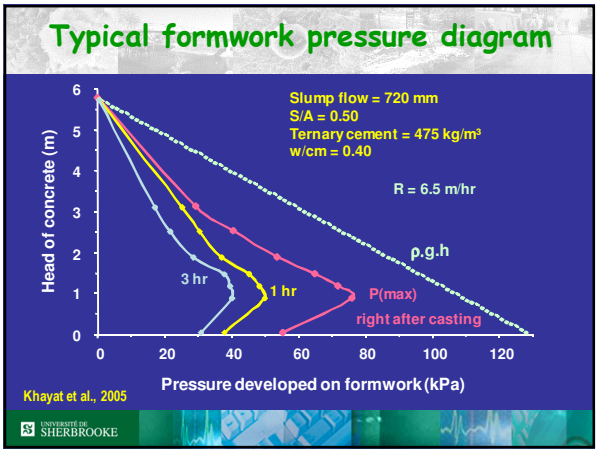

Field validation
H = 5.5 - 6 m
L = 7 m
W = 0.19 m
As = 0.4%
7 pressure sensors


Typical formwork pressure diagram
Slump flow = 720 mm
S/A = 0.50
Ternary cement = 475 kg/m³
w/cm = 0.40
R = 6.5 m/hr
ρ.g.h
3 hr
1 hr
P(max)
right after casting
Head of concrete (m)
Pressure developed on formwork (kPa)
Khayat et al., 2005
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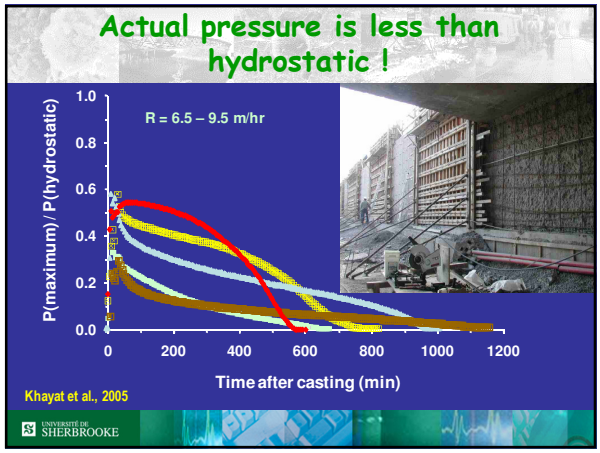
Actual pressure is less than hydrostatic !
R = 6.5 – 9.5 m/hr
P(maximum)/ P(hydrostatic)
Time after casting (min)
Khayat et al., 2005
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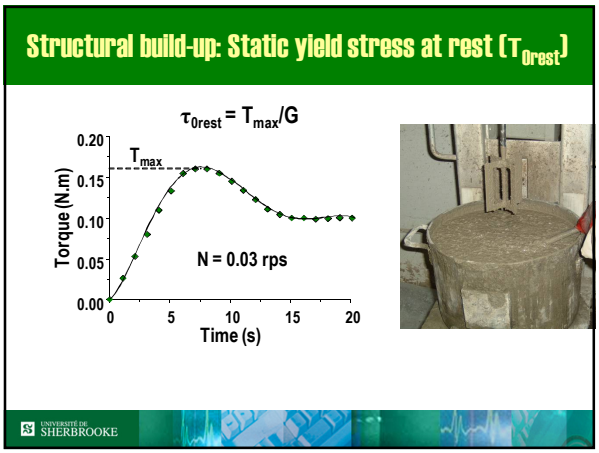
Structural build-up: Static yield stress at rest (τ_{0rest})
$\tau_{0rest} = T_{max}/G$
T_{max}
Torque (N.m)
Time (s)
N = 0.03 rps
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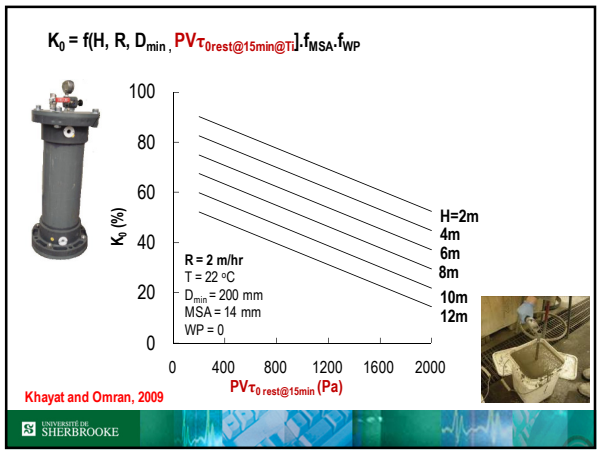
$K_0 = f(H, R, D_{min}, PV\tau_{0rest@15min@Ti}).f_{MSA}.f_{WP}$
K_0 (%)
H=2m
4m
6m
8m
10m
12m
R = 2 m/hr
T = 22 °C
D_{min} = 200 mm
MSA = 14 mm
WP = 0
$PV\tau_{0\,rest@15min}$ (Pa)
Khayat and Omran, 2009
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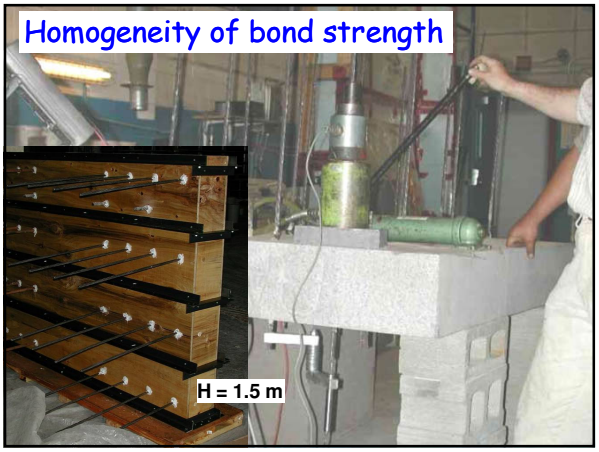
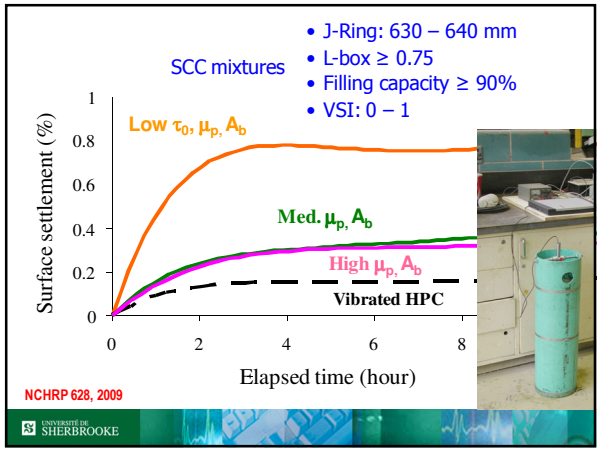

Homogeneity of bond strength
H = 1.5 m


SCC mixtures
• J-Ring: 630 – 640 mm
• L-box ≥ 0.75
• Filling capacity ≥ 90%
• VSI: 0 – 1
Low τ_0, μ_p, A_b
Med. μ_p, A_b
High μ_p, A_b
Vibrated HPC
Surface settlement (%)
Elapsed time (hour)
NCHRP 628, 2009
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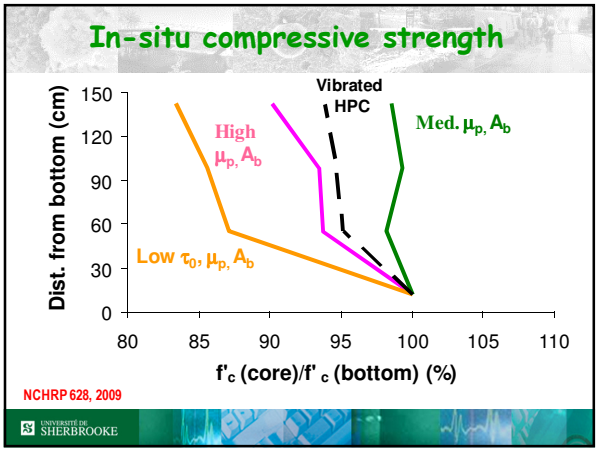
In-situ compressive strength
Vibrated HPC
High μ_p, A_b
Med. μ_p, A_b
Low τ_0, μ_p, A_b
Dist. from bottom (cm)
f'c (core)/f' c (bottom) (%)
NCHRP 628, 2009
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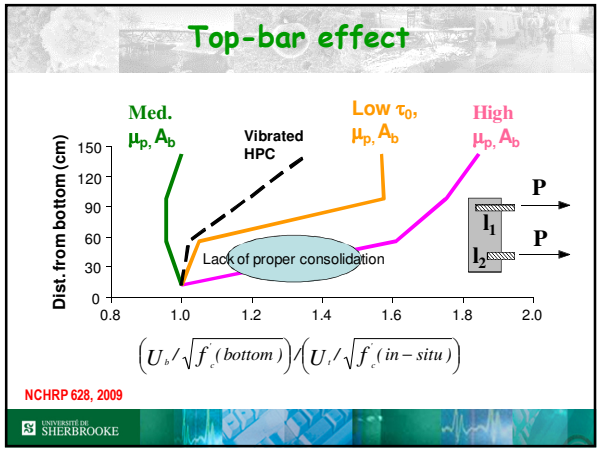
Top-bar effect
Med. μ_p, A_b
Vibrated HPC
Low τ_0, μ_p, A_b
High μ_p, A_b
Lack of proper consolidation
P
P
l_1
l_2
Dist. from bottom (cm)
$(U_b/\sqrt{f'_c(bottom)})/(U_t/\sqrt{f'_c(in-situ)})$
NCHRP 628, 2009
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Recommended values to ensure homogeneous properties

Static stability	Maximum surface settlement ≤ 0.5% Column segregation index (Iseg) ≤ 5% Percent static segregation (S) ≤ 15
Viscosity	Plastic viscosity ≤ 0.073 psi.s (500 Pa.s) *(Modified Tattersall two-point rheometer with vane device)*
Mechanical properties	Core-to-cylinder compressive strength ≥ 90% (similar curing conditions) Bond strength modification factor ≤ 1.4

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