Evaluation of Thixotropy of SCC and Inflence on Concrete Perfomance

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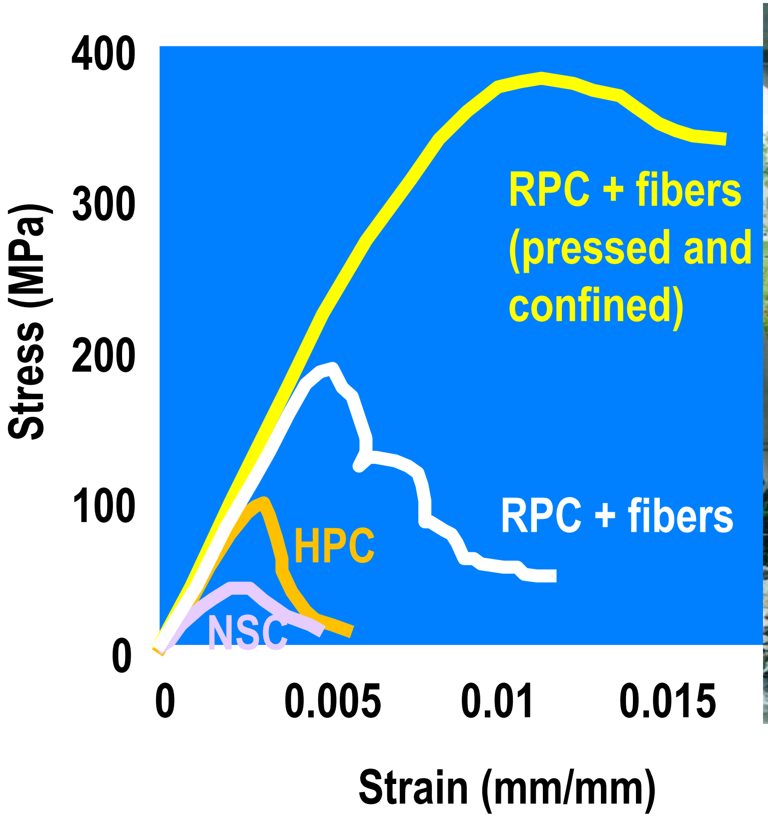
HPC: Concrete with improved mechanical properties & service life



230-MPa RPC foot bridge, Sherbrooke

Confederation Bridge, N.B. – PEI
100-year design life

HPC: Concrete with improved workability

UNIVERSITÉ DE
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NSERC
CRSNG

Industrial Research Chair on High-Performance Flowable Concrete with Adapted Rheology (FCAR)

Owners:

Ministère des Transports Québec

Ville de Montréal

Hydro Québec

Material Suppliers:

Association Canadienne du Ciment
Cement Association of Canada

Holcim

OMYA

HC HANDY CHEMICALS LTD.

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Engineering Firms:

SNC • LAVALIN

TEKNIKA HBA

Testing Labs:

QUALITAS
La force du groupe

LES LABORATOIRES SHERMONT
Membre de TEKNIKA HBA

SM

Inspecsol

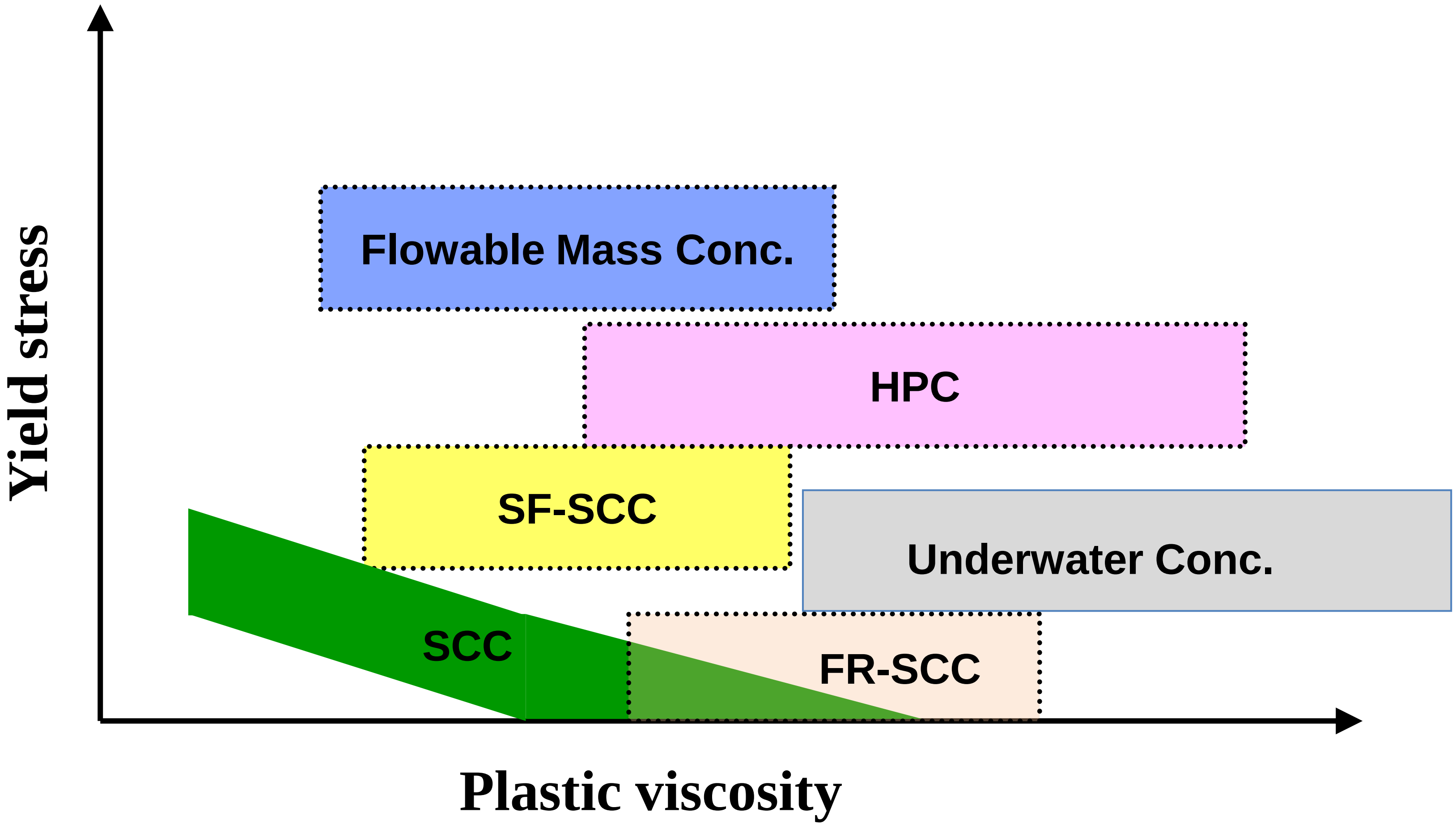
LVM TECHNISOL

Laboratoire A.B.S. Inc.

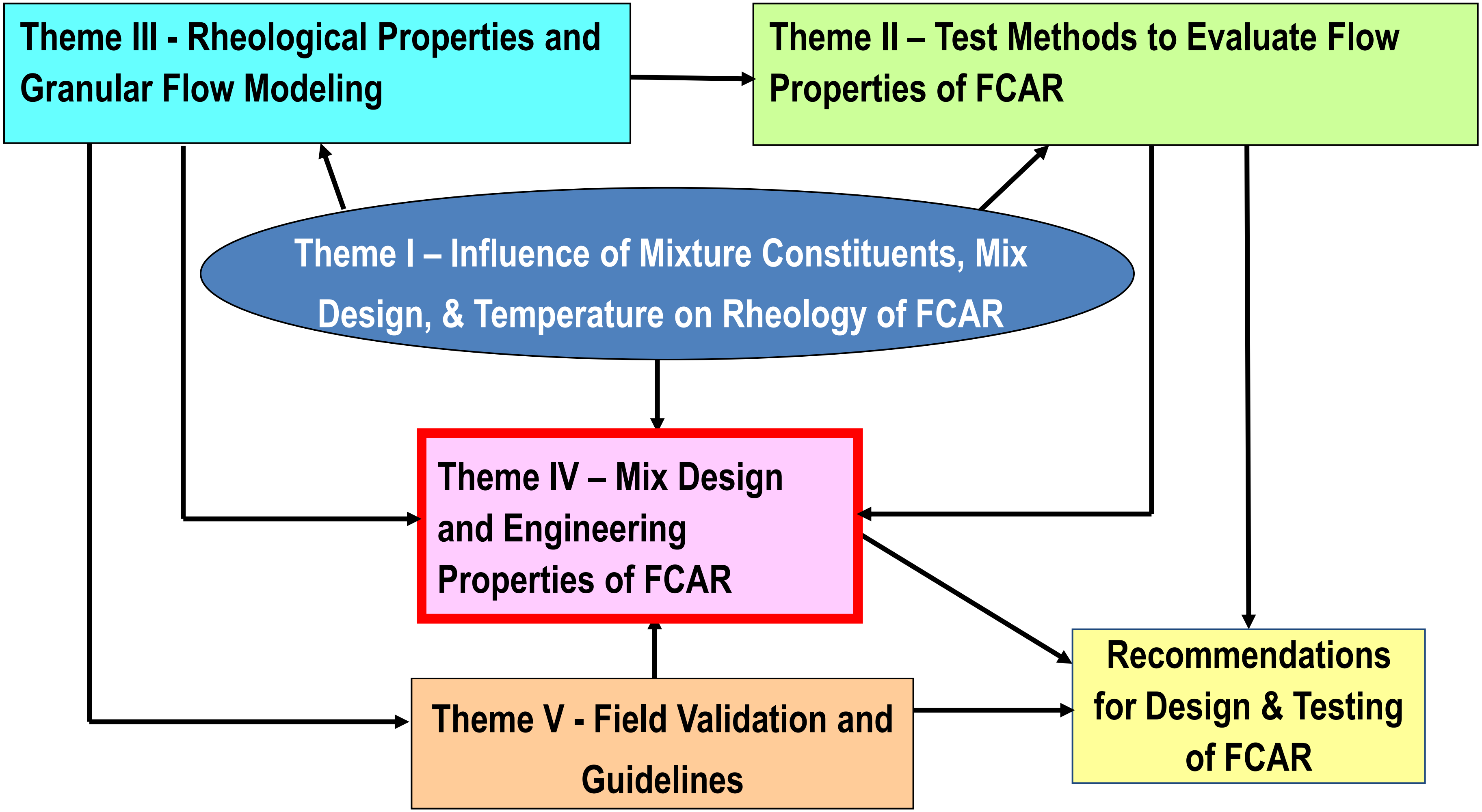
Prefab:

SARAMAC
BÉTON PRÉFABRIQUÉ
ARCHITECTURAL
& STRUCTURAL

Rheological parameters of FCAR



IRC Research Program



Theme III - Rheological Properties and Granular Flow Modeling

Theme II – Test Methods to Evaluate Flow Properties of FCAR

Theme I – Influence of Mixture Constituents, Mix Design, & Temperature on Rheology of FCAR

Theme IV – Mix Design and Engineering Properties of FCAR

Recommendations for Design & Testing of FCAR

Theme V - Field Validation and Guidelines

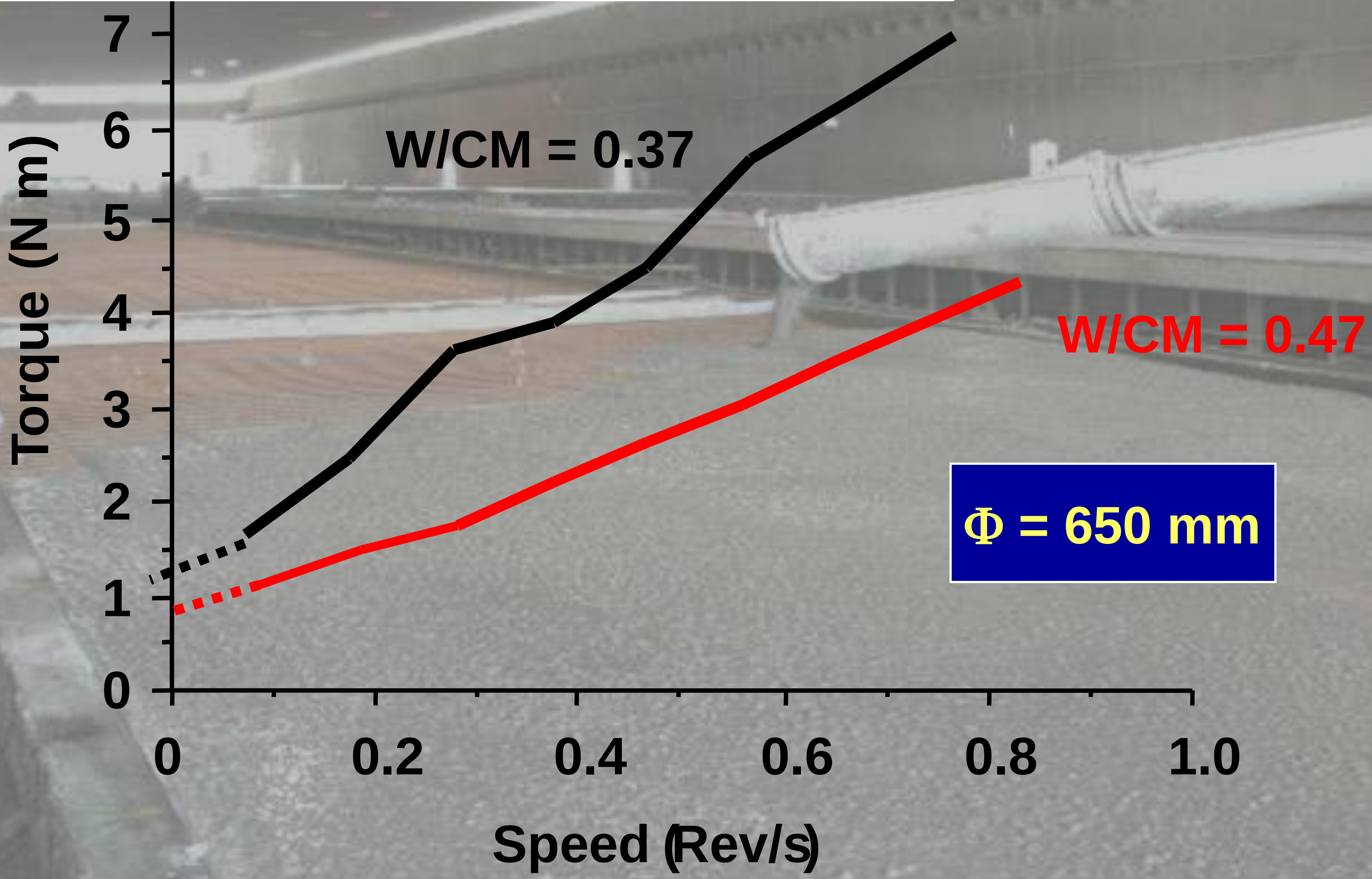
Flow behavior of SCC is complex and must be optimized to secure adequate performance

low resistance to flow (low τ_0)

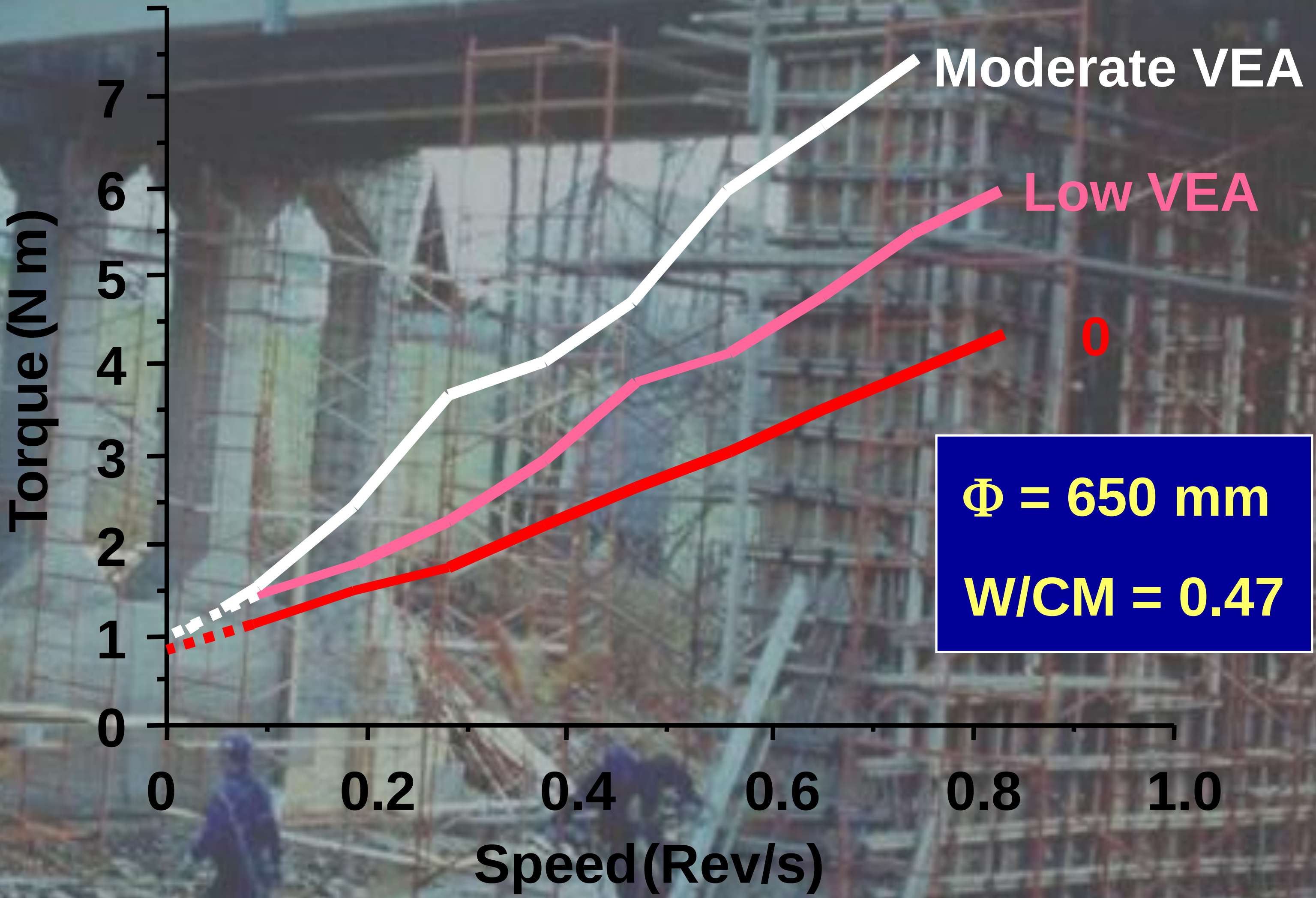
high stability (moderate visc.)

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

Reduce water content to enhance viscosity



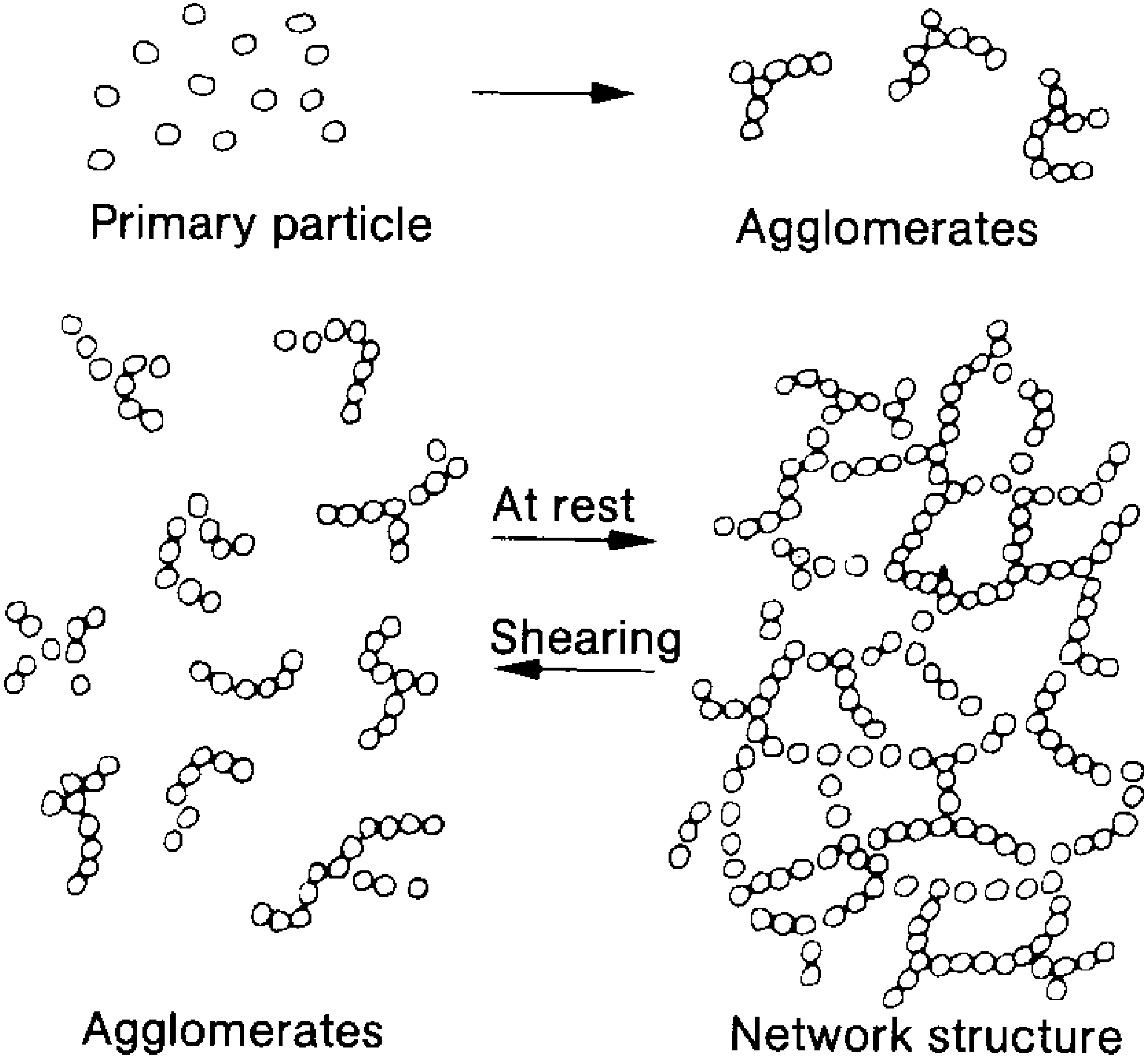
Incorporate VEA to enhance viscosity



Φ = 650 mm

W/CM = 0.47

Thixotropy – variation of viscosity with time at constant shear rate (reversable)

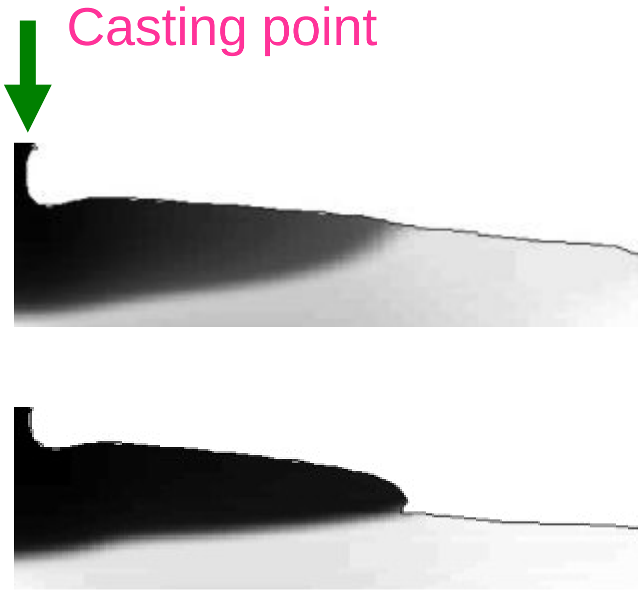


Negative Aspects of Structural Build-up

Multi-layer casting

After 5 min of rest time, the 2 layers can mix well

After 20 min of rest time, the 2 layers do not mix at all

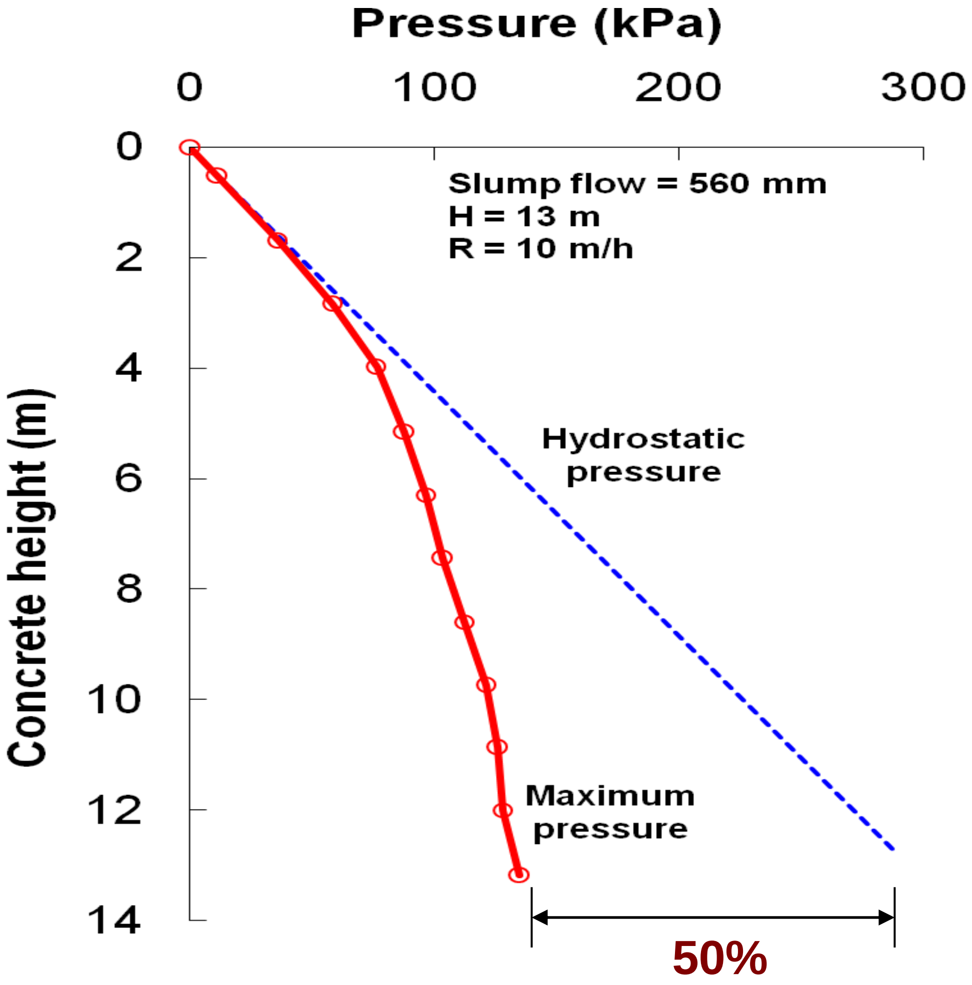


Negative aspect of structural build-up (thixotropy)

Positive Aspects of Structural Build-up

Reduction in formwork pressure after casting due to structural build-up at rest

Improved static stability

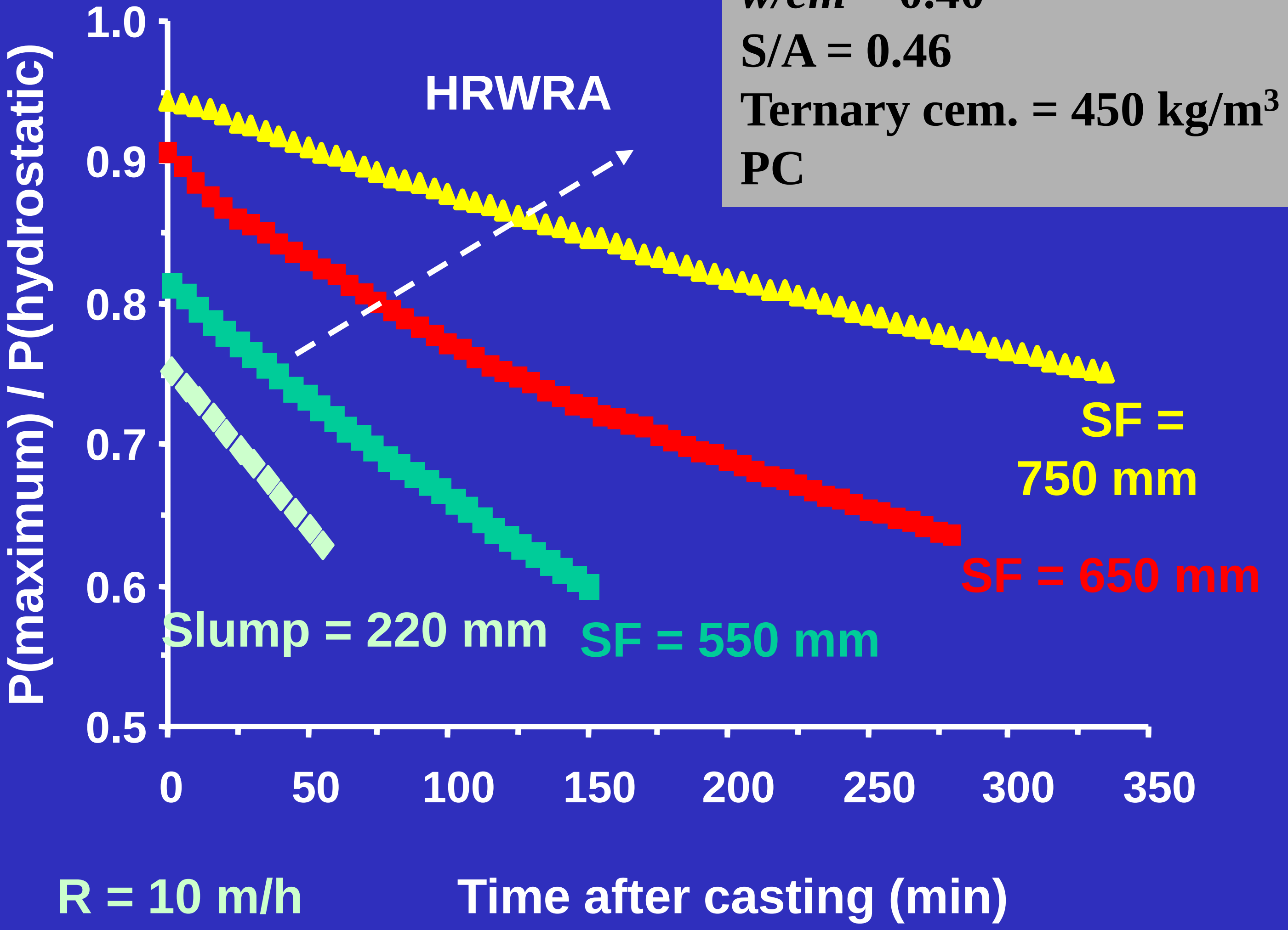


Factors Affecting Form Pressure of CVC

- **Fluidity level**
- **Casting rate**
- **Coarse aggregate volume**
- **Binder content and type**
- **Presence of admixtures**
- **Temperature of fresh concrete**
- **Minimum dimension of formwork**
- **Degree of vibration**
- **Etc.**

Effect of Consistency Level

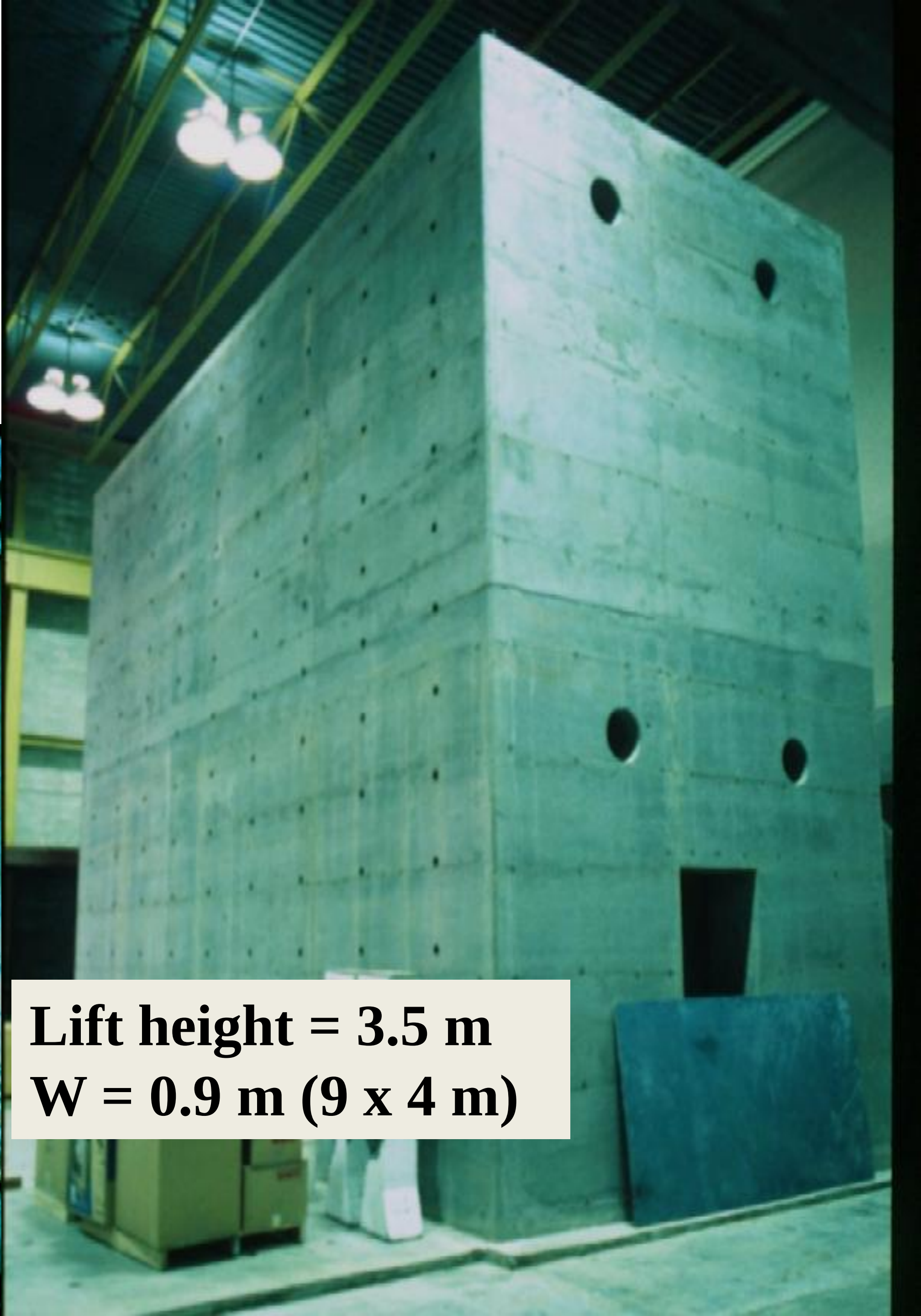
w/cm = 0.40
S/A = 0.46
Ternary cem. = 450 kg/m^3
PC



H = 2.8 m

D = 200 mm

R ~ 1 m/hr



Lift height = 3.5 m

W = 0.9 m (9 x 4 m)

Lift height = 2.8 - 3 m

W = 0.2 m

R ~ 2 m/hr

Lift height > 3 m

W = 0.15 m

R ~ 8-10 m/hr

ACI 347-04 [Hurd, 2002]

Normal concrete with slump < 175 mm at time of casting

Immersion of vibrator < 1.2 m in fresh concrete. Underneath concrete is not re-vibrated

$R \leq 4.5$ m/h

- Columns (R and H *not specified*) or walls with $R < 2.1$ m/h, $H \leq 4.2$ m

$$p_{\max}(\mathrm{kPa}) = C_w C_c \left[7.2 + \frac{785R}{T+17.8} \right]$$

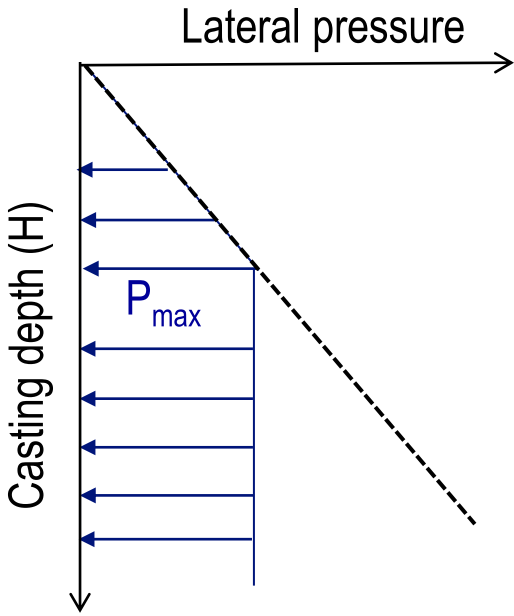
C_w : Unit weight coefficient C_c : Chemistry coefficient

- Walls ($R < 2.1$ m/h, $H > 4.2$ m) or walls $2.1 < R < 4.5$ m/h, H *not specified*

$$p_{\max}(\mathrm{kPa}) = C_w C_c \left[7.2 + \frac{1156}{T+17.8} + \frac{244R}{T+17.8} \right]$$

$$30\,C_w\ (\mathrm{kPa}) \leq P_{\max} \leq 150 C_w\ C_c\ (\mathrm{kPa})$$

$$P_{\max} \leq \gamma_c H$$



- Pumping from bottom:

$P_{max} = \gamma_c H$ + 25% pump surge pressure

Modified ACI 347-04 [Hurd, 2002]

Density (kg/m^3)	C_w : *Unit weight coefficient*
< 2240	$C_w = 0.5\,[1 + w/2320] \geq 0.80$
2240 -2400	$C_w = 1.0$
> 2400	$C_w = w/2320$ kg/m^3

C_c: Chemistry coefficient		C_c
Cement type or blend	Type I, II, III without **retarders**	1.0
	Type I, II, III with retarders	1.2
	Other types or blends containing **<** 70% slag or 40% FA without retarder	
	Other types or blends containing **<** 70% slag or 40% FA with retarder	1.4
	Blends containing **>** 70% slag or 40% FA	

Retarders (set retarder, retarder water reducer, retarding midrange WRA, or HRWRA) that delay setting

Various models to evaluate lateral

	R	T	H	Form width	Time	ρ	Thixotropy	Slump	Set time	Waiting period
1- ACI 347-04	x	x	x			x				
2- U.K. (CIRIA Report 108)	x	x	x			x				
3- Japan - Standard Specifications for Concrete Structures (2002)	x	x	x			x				
4- Sweden (Design of Vertical Concrete Formwork)	x	x							x	

R = Rate of casting
T = Temperature
H = Casting depth

Various models to evaluate lateral

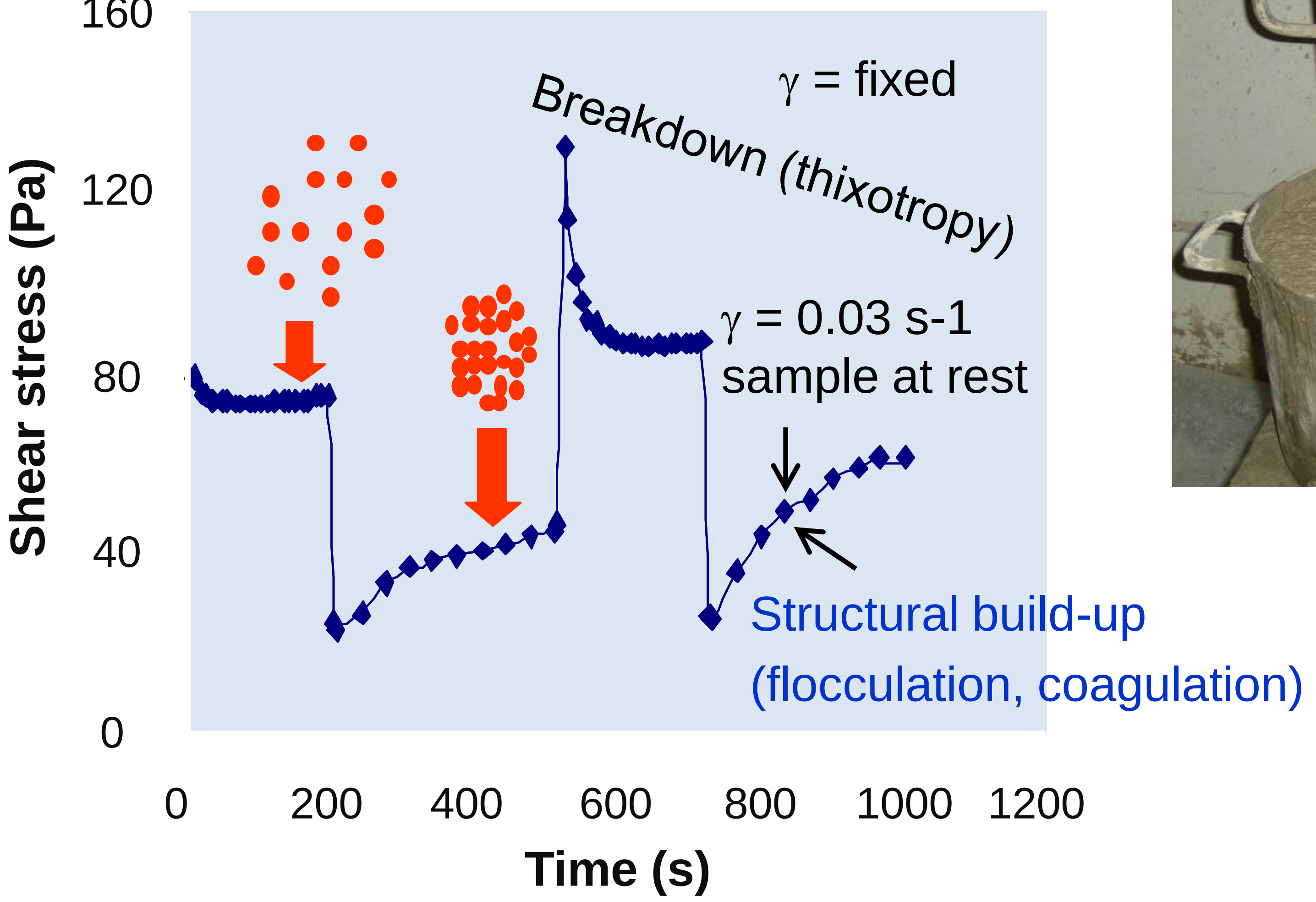
	R	T	H	Form width	Time	ρ	Thixotropy	Slump	Set time	Waiting period
1- ACI 347-04	x	x	x			x				
2- U.K. (CIRIA Report 108)	x	x	x			x				
3- Japan - Standard Specifications for Concrete Structures (2002)	x	x	x			x				
4- Sweden (Design of Vertical Concrete Formwork)	x	x							x	
5- Khayat & Assaad [2005]	x		x			x	x			
6- Roussel and Ovarlez [2005]	x		x	x		x	x			
7- Lange et al., [2005]	x		x		x	x				
8- Khayat & Omran [2009]	x	x	x	x		x	x			x
9- DIN 18 218 :2010-01 (2010)	x		x			x			x	
10- Gardner et al., 2011	x				x	x		S-flow loss		

R = Rate of casting
T = Temperature
H = Casting depth

Outline

- Thixotropy determination: structural breakdown and structural build-up at rest
- Thixotropy vs. form pressure exerted by SCC
- Structural build-up vs. drop in interlayer bond

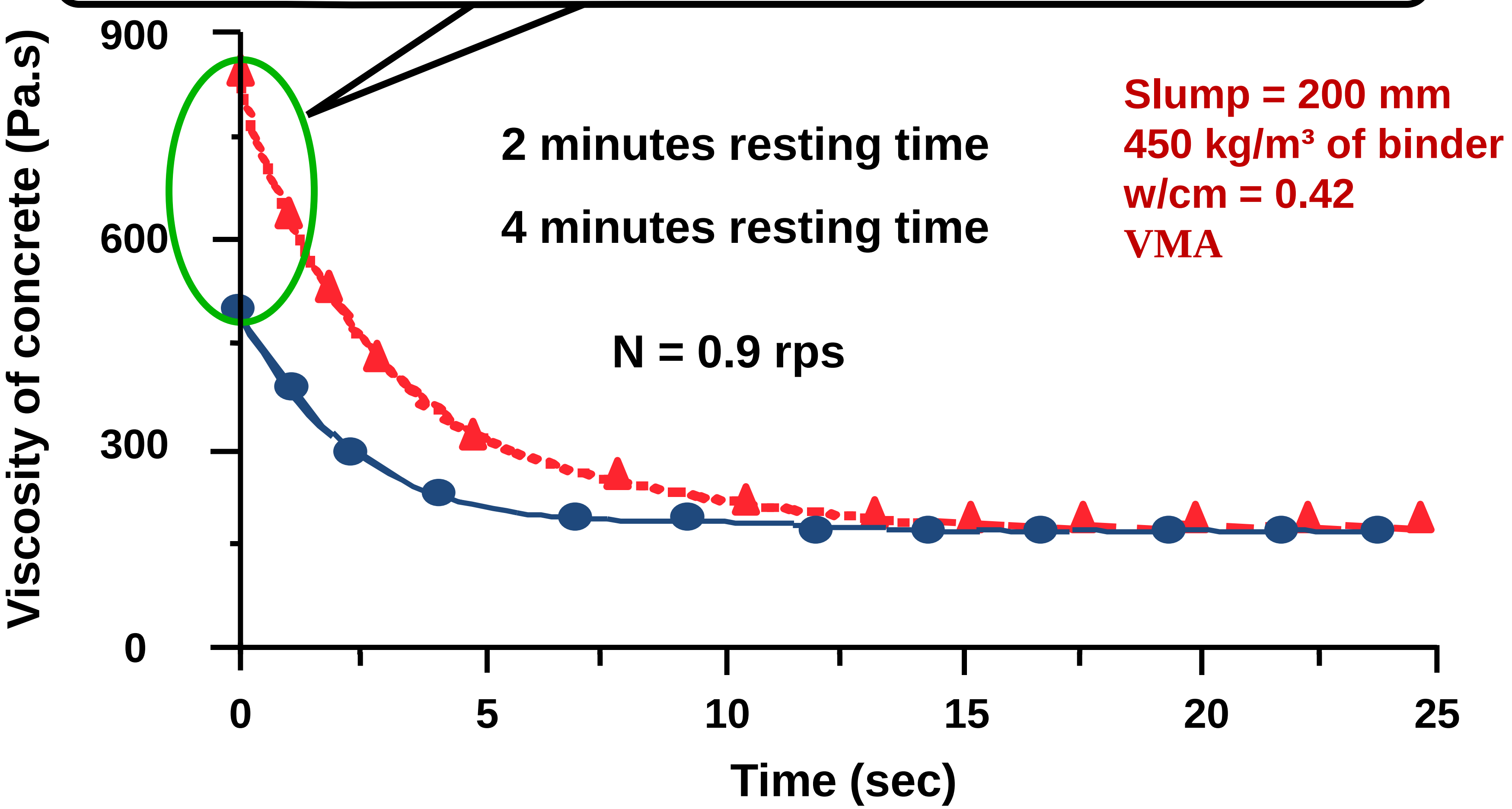
Thixotropy – variation of viscosity (or shear stress) with time under constant shear rate - structural build-up when left at rest (reversible)



Modified MK-III rheometer

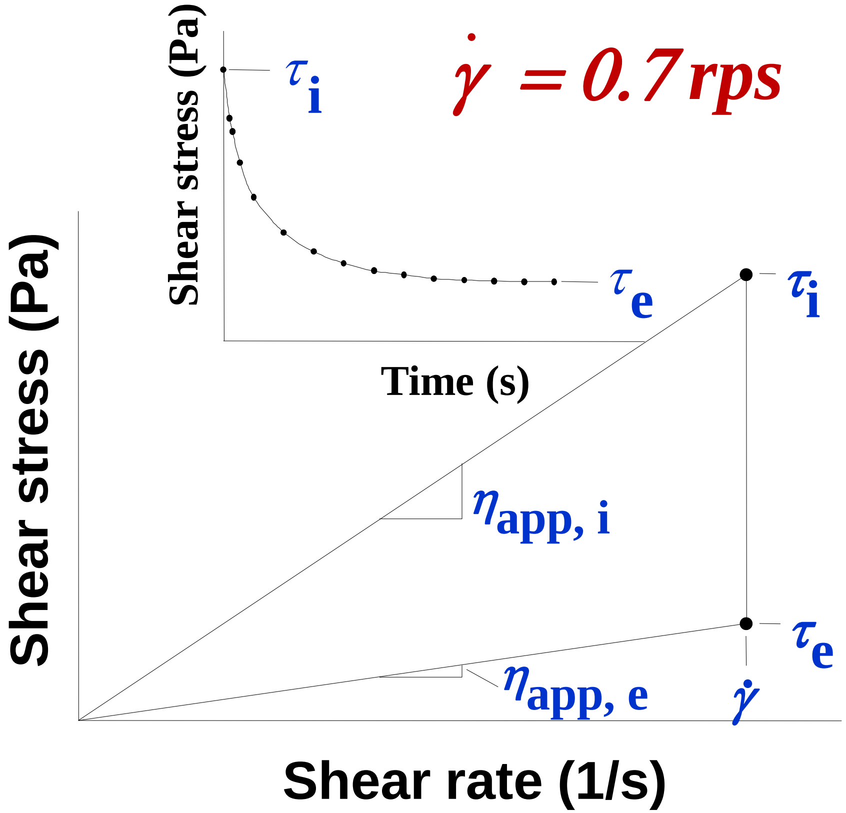
Importance of Restructuring !!

Formwork pressure = f (restructuring of the concrete)

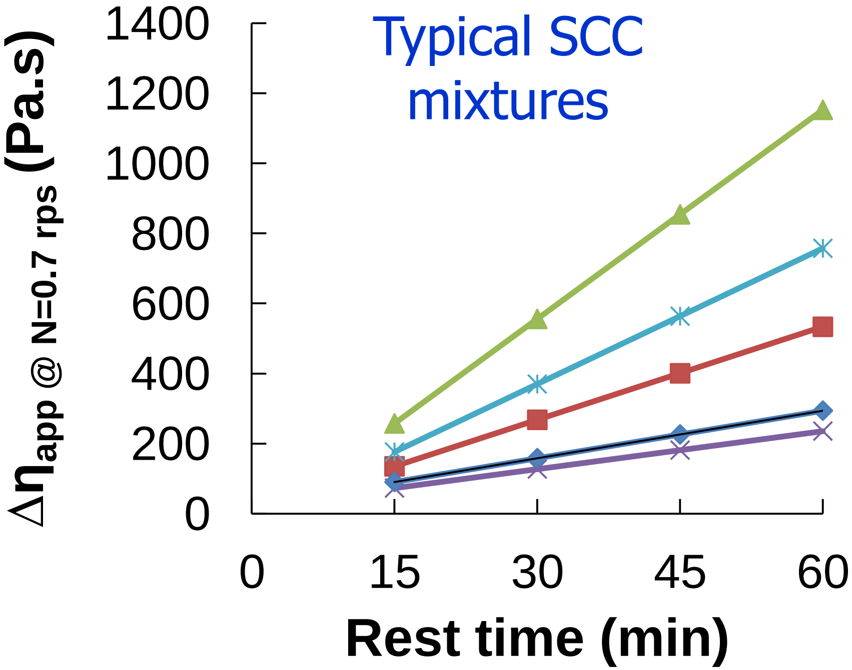


Slump = 200 mm
450 kg/m³ of binder
w/cm = 0.42
VMA

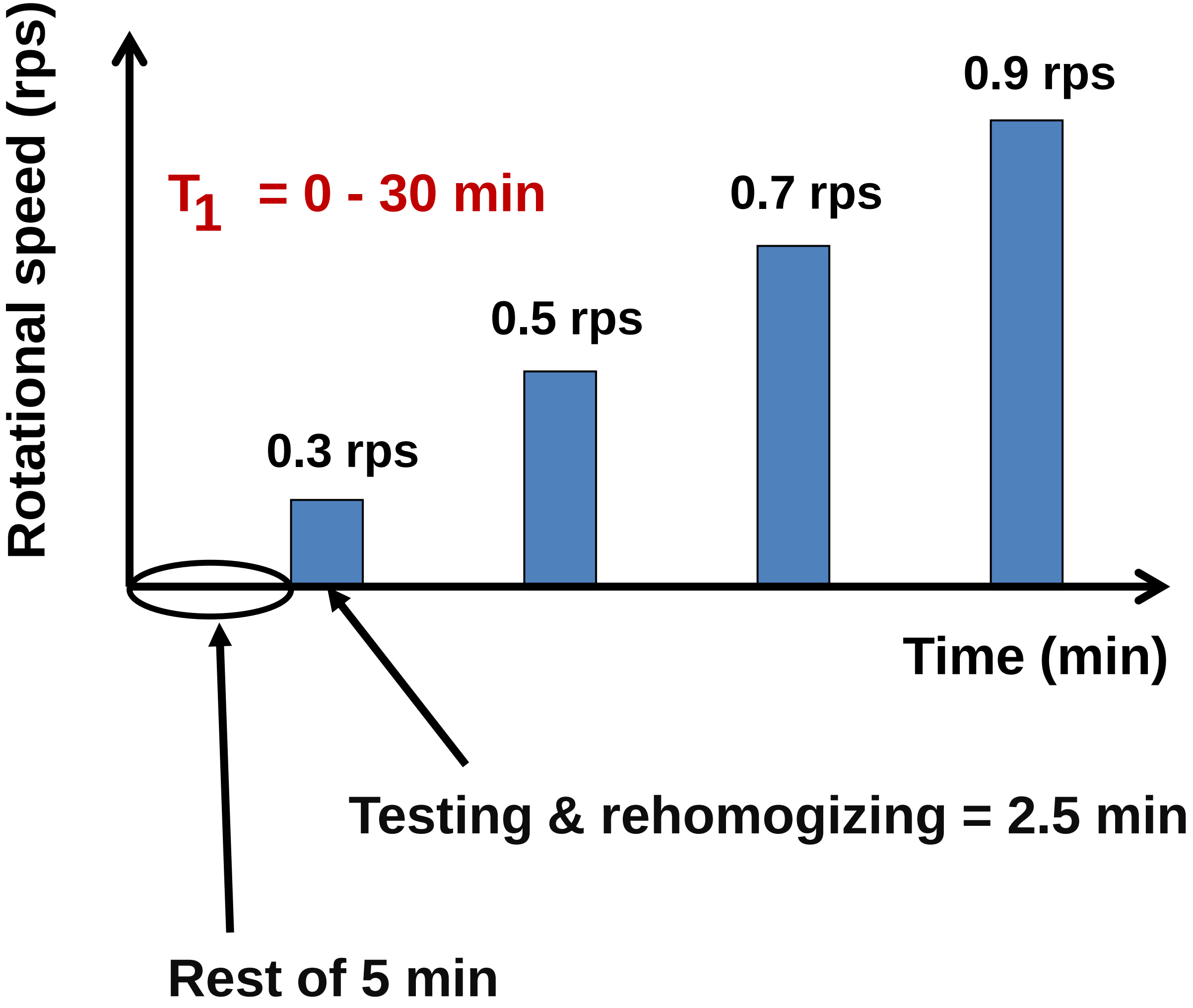
1. Structural breakdown: drop in app. viscosity ($\Delta\eta_{app}$)



$$\Delta\eta_{app} = \frac{\tau_i - \tau_e}{\dot{\gamma}}$$



Time intervals for assessing thixotropy

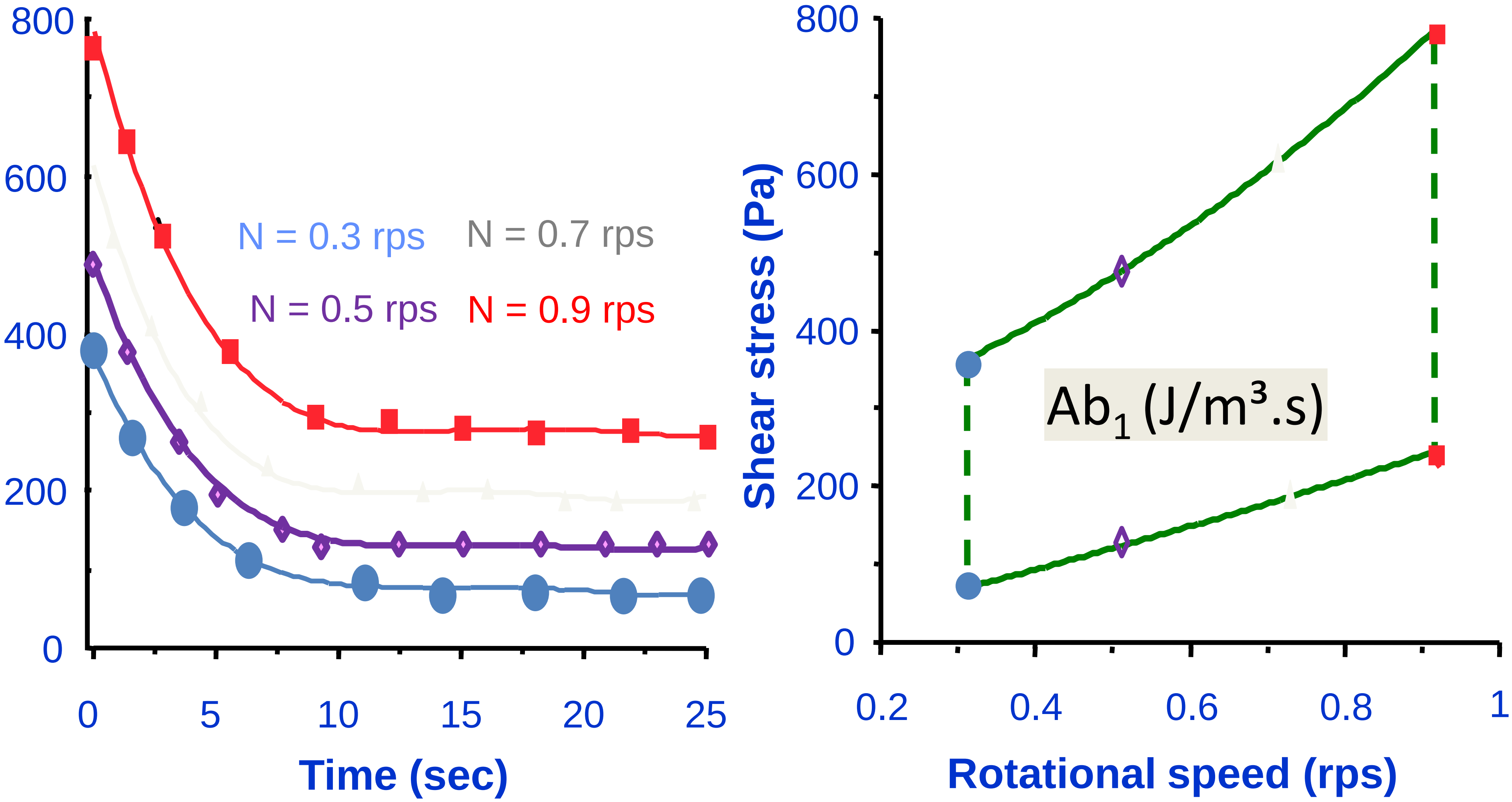


T_1 = 0 - 30 min

Testing & rehomogizing = 2.5 min

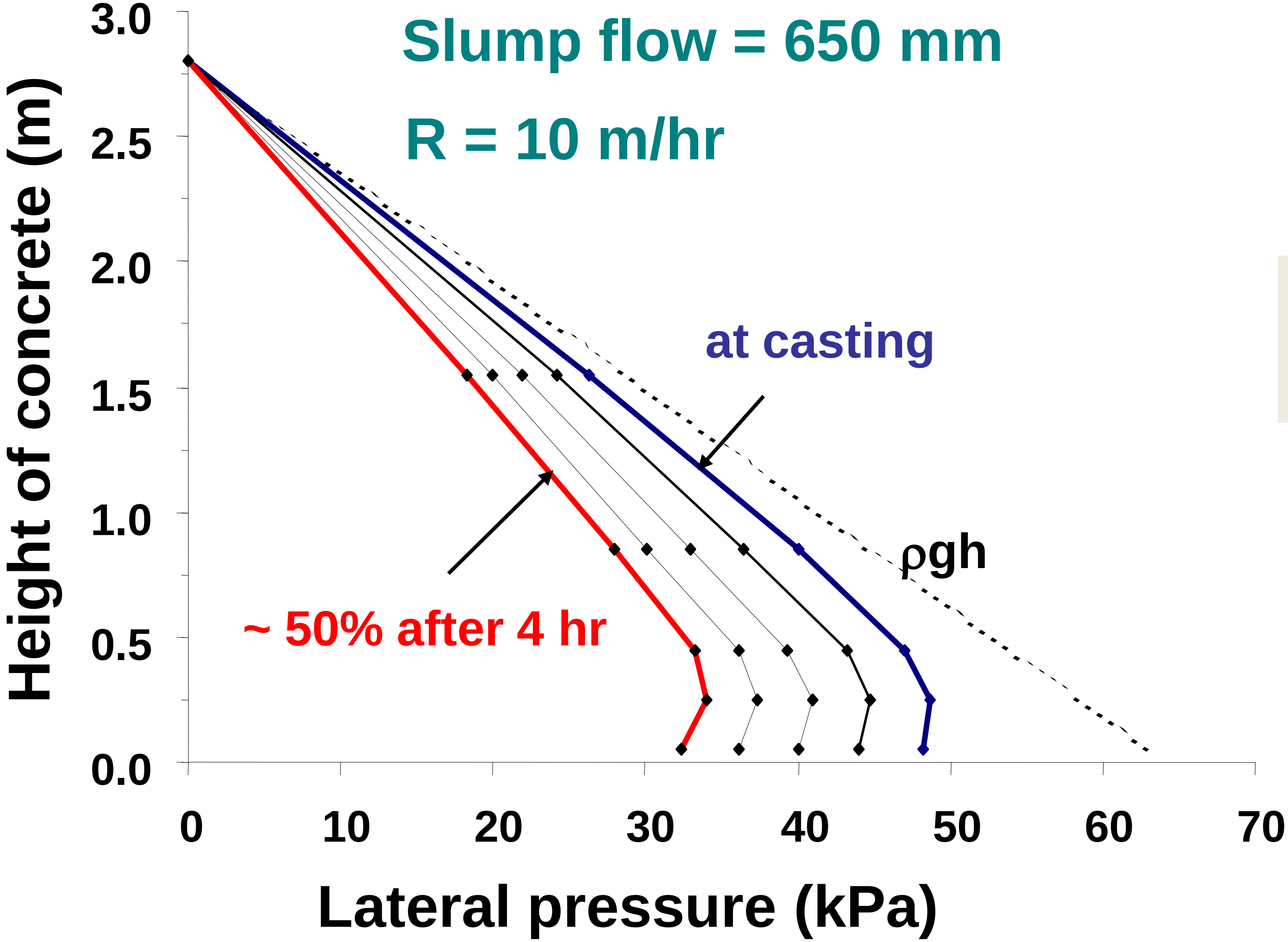
Rest of 5 min

1. Structural breakdown: structural breakdown area (Ab_1)



Lapasin et al. [1983] $Ab_1 = \int_{0.3}^{0.9} (\tau_i(N) - \tau_e(N))\, dN \quad J/m^3.s$

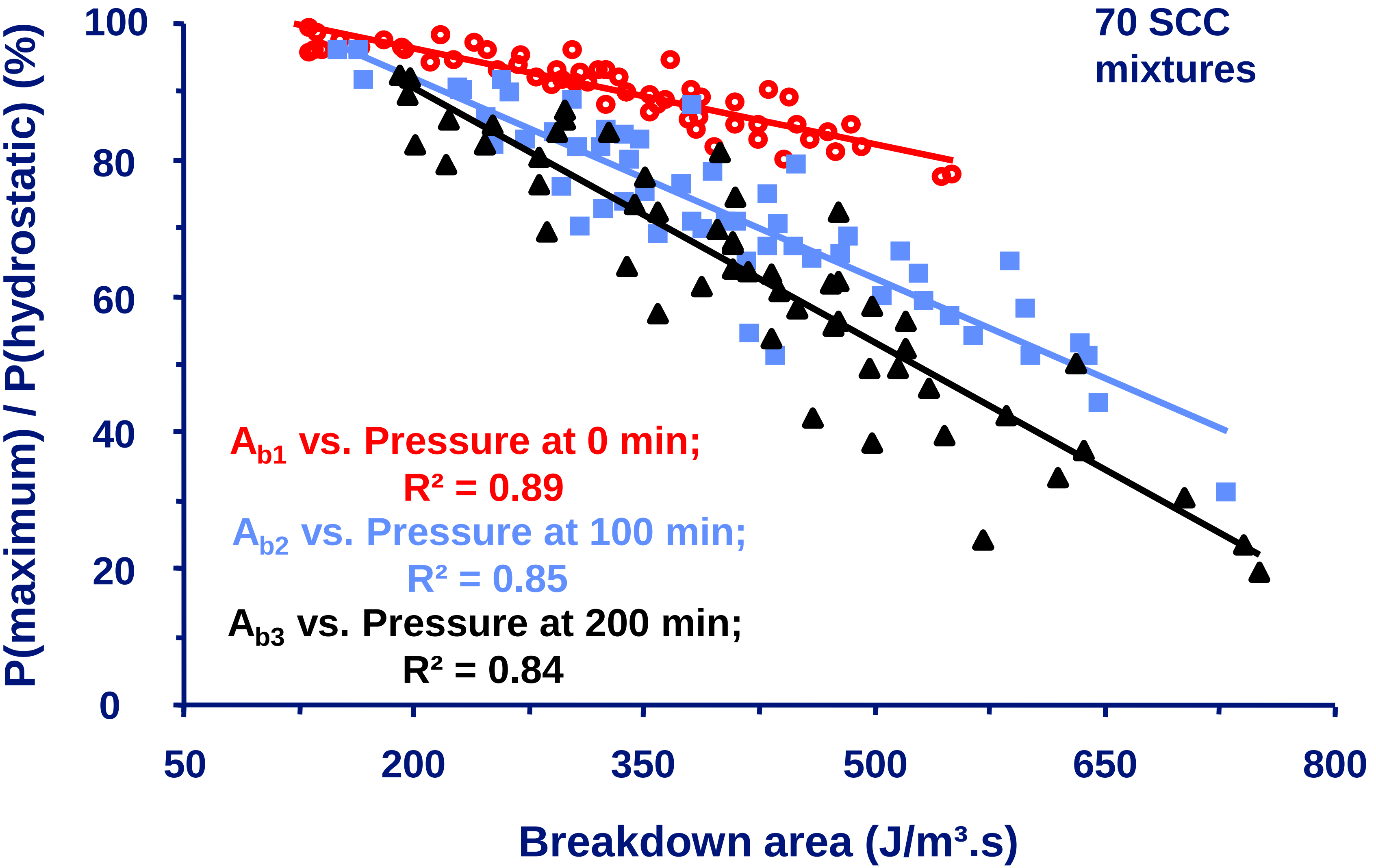
Lateral pressure envelope of SCC



H = 2.8 m

D = 200 mm

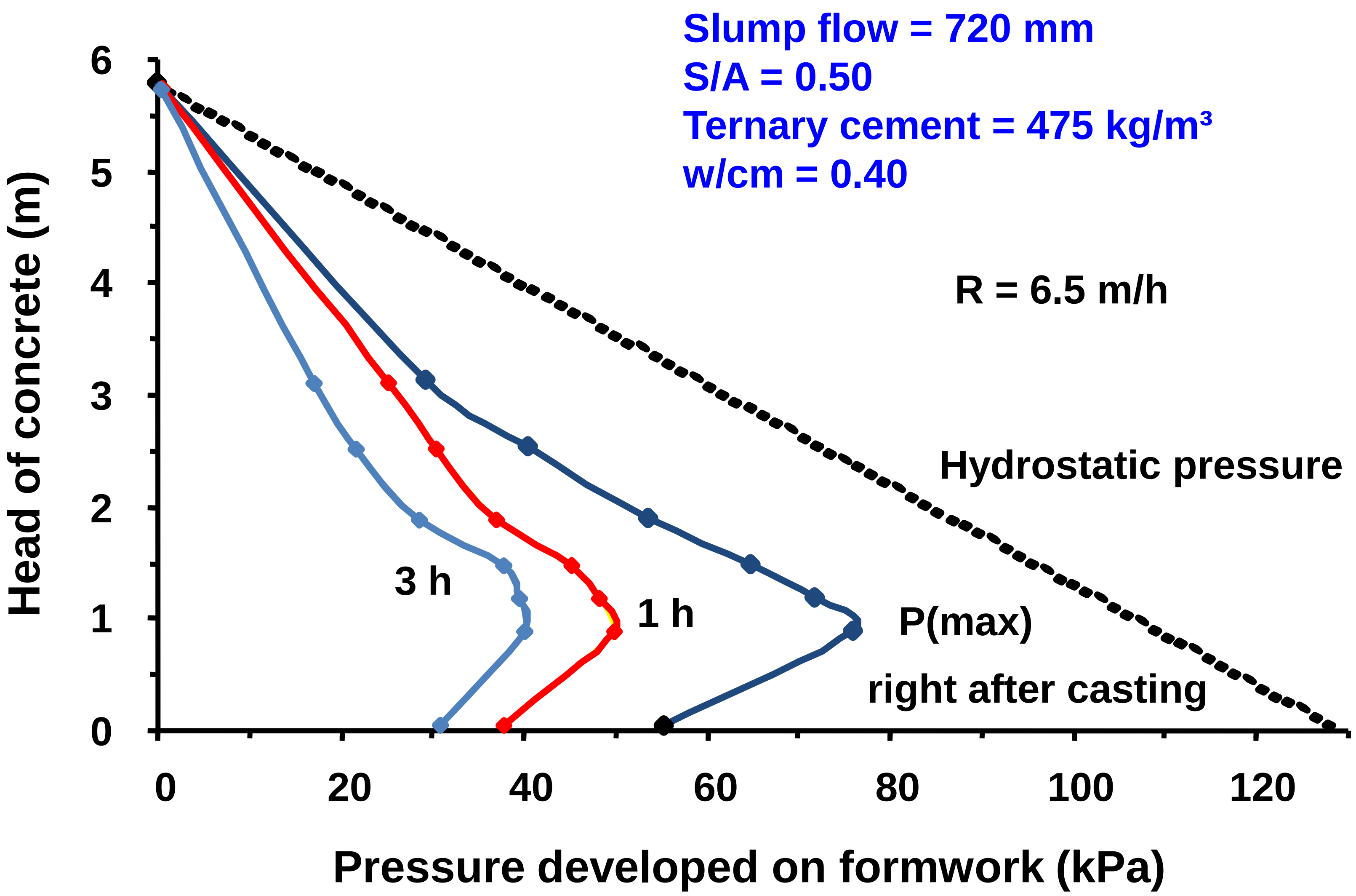
Thixotropy vs. Lateral Pressure



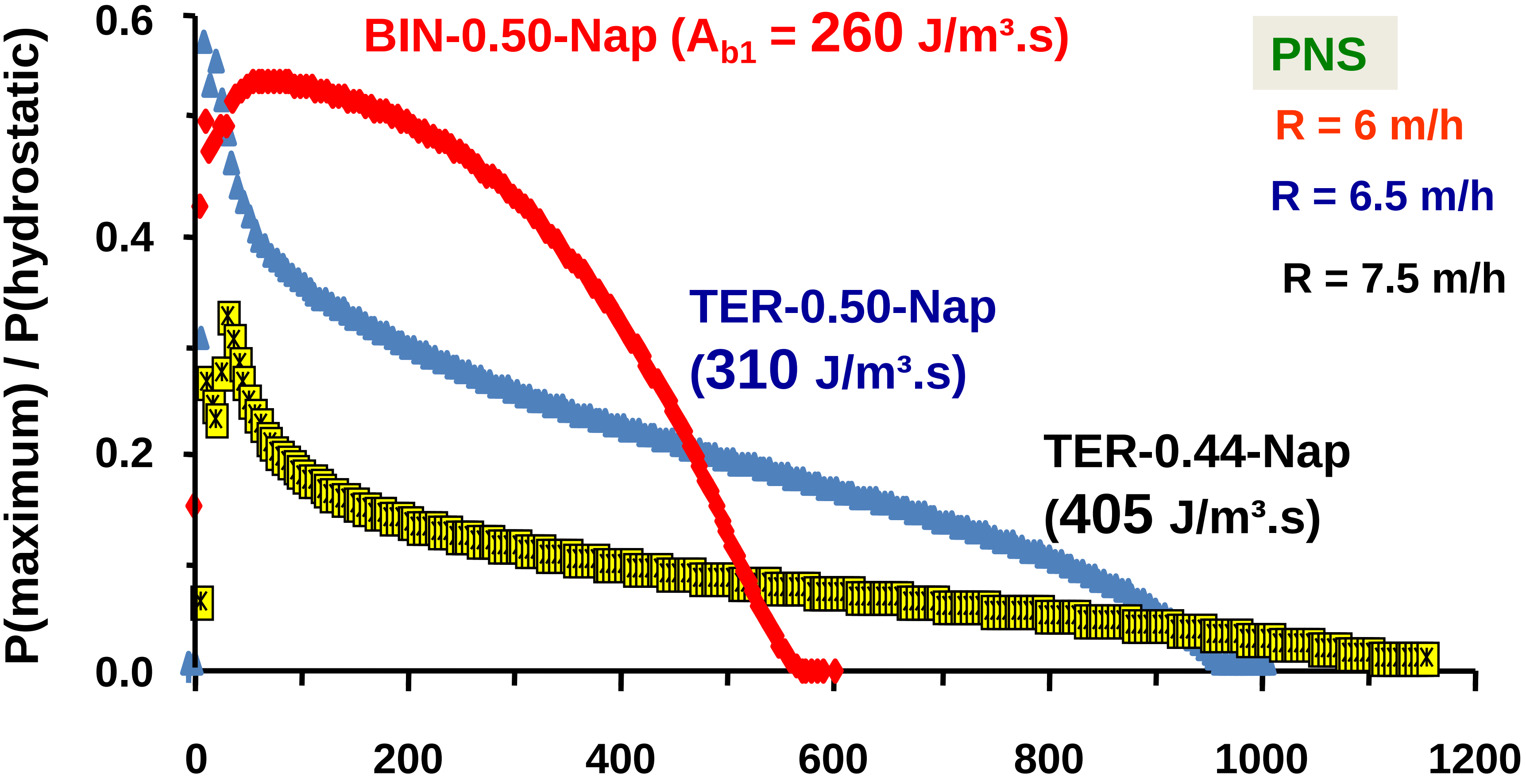
R ~ 6-10 m/hr

ÉCONOMISEZ LA COMMISSION DU CONCESSIONNAIRE
MTL AUTO PRIX
1956
RASUCO
CATERPILLAR
CAT
3423

Typical Formwork Pressure Diagram

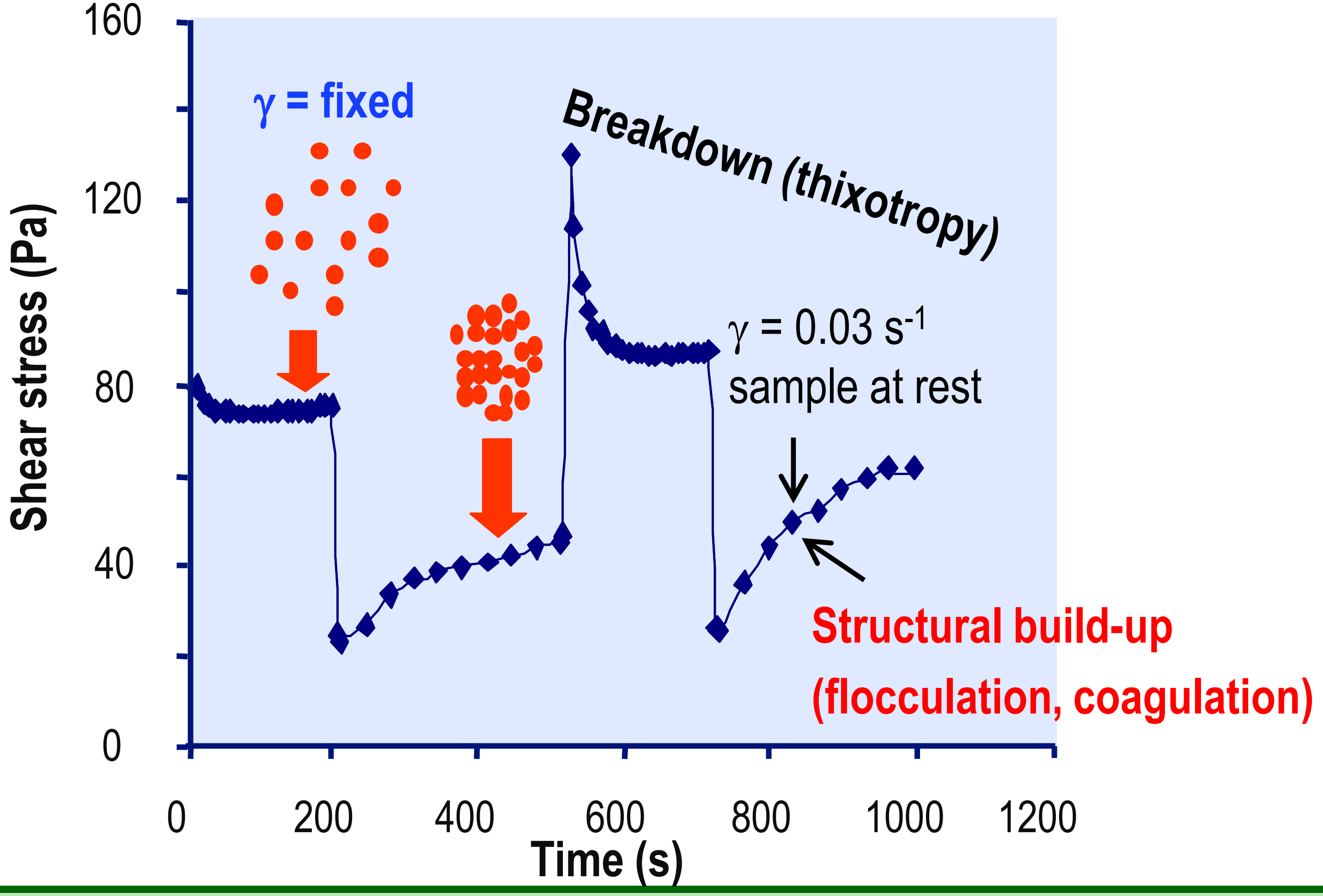


Pressure Variations with Thixotropy

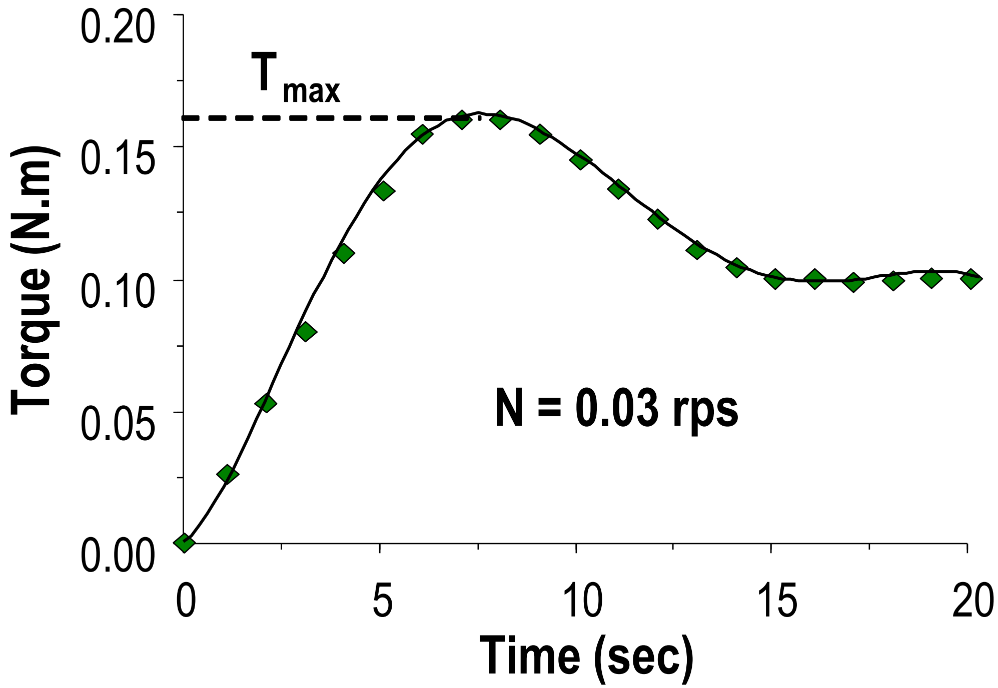


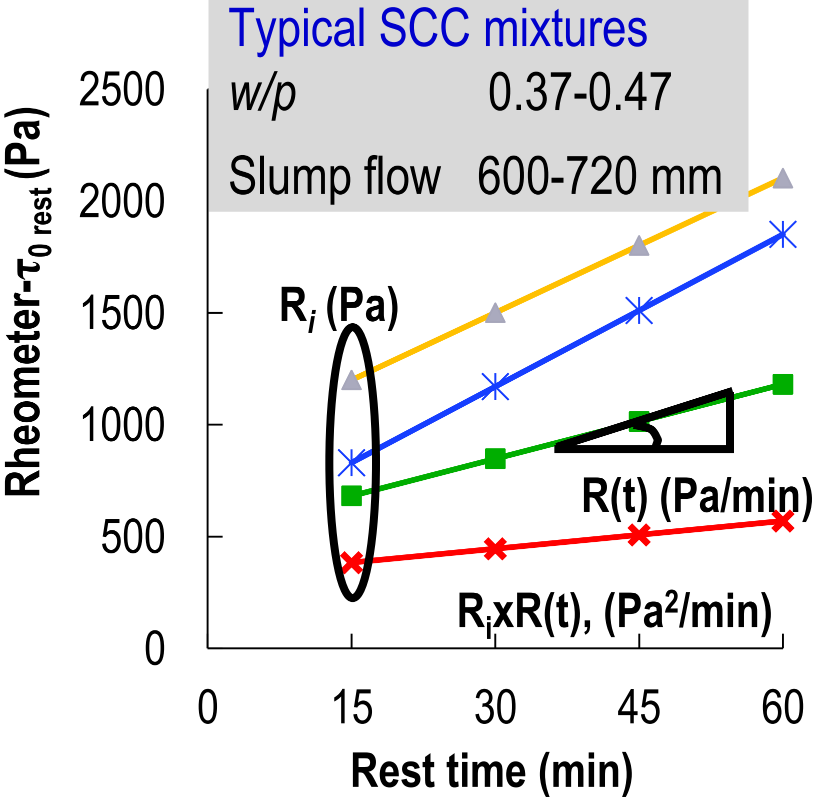
2. Structural build-up at rest: Re-structuring

Structural build-up: increase in shear stress (or viscosity) when the material is left at rest



Static shear stress at rest (τ_{0rest})





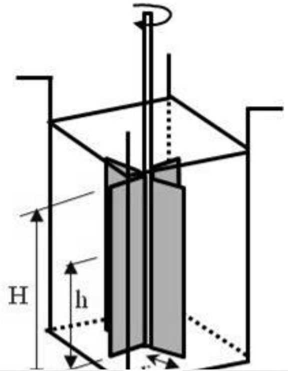
Typical SCC mixtures

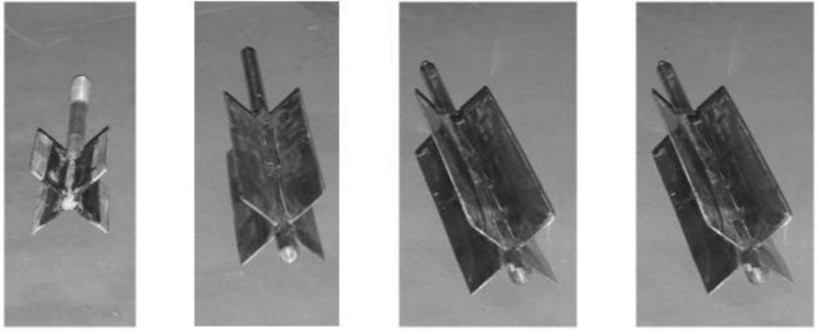
w/p 0.37-0.47

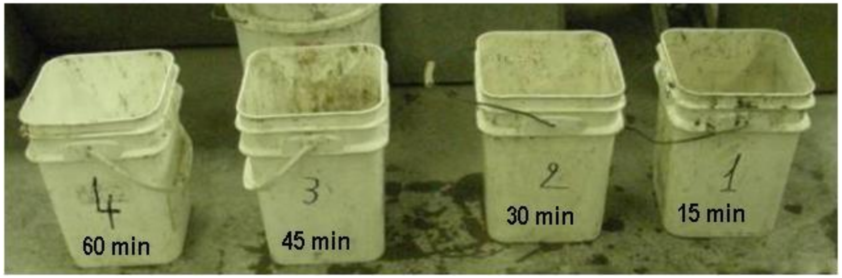
Slump flow 600-720 mm

Portable vane (PV) test

$$\tau_{0rest} = T_{max} / G$$







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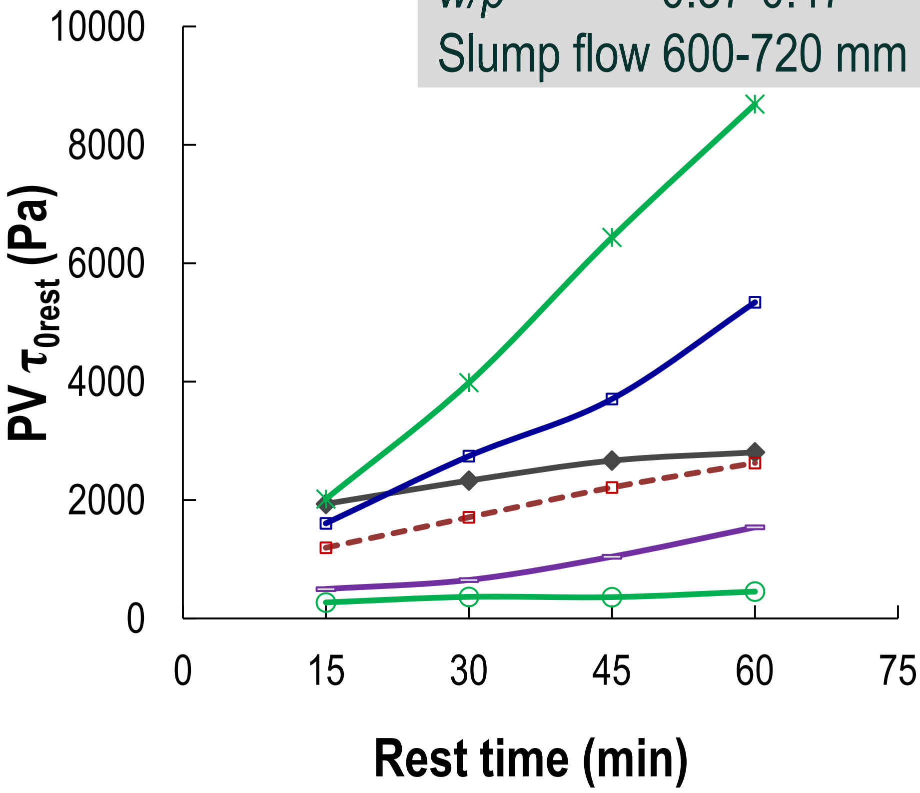
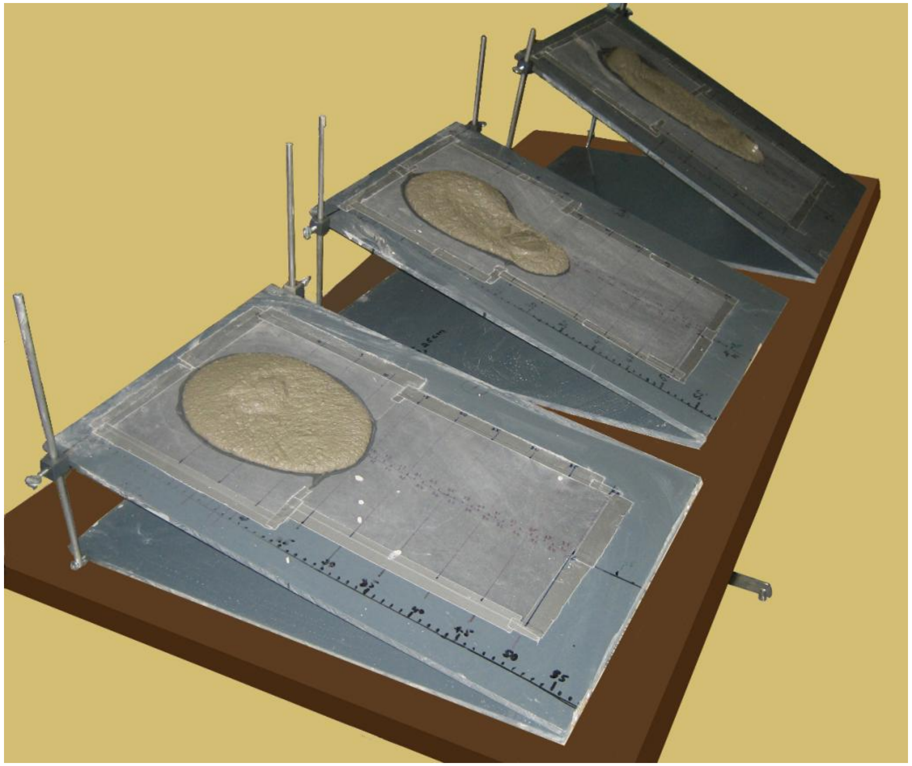
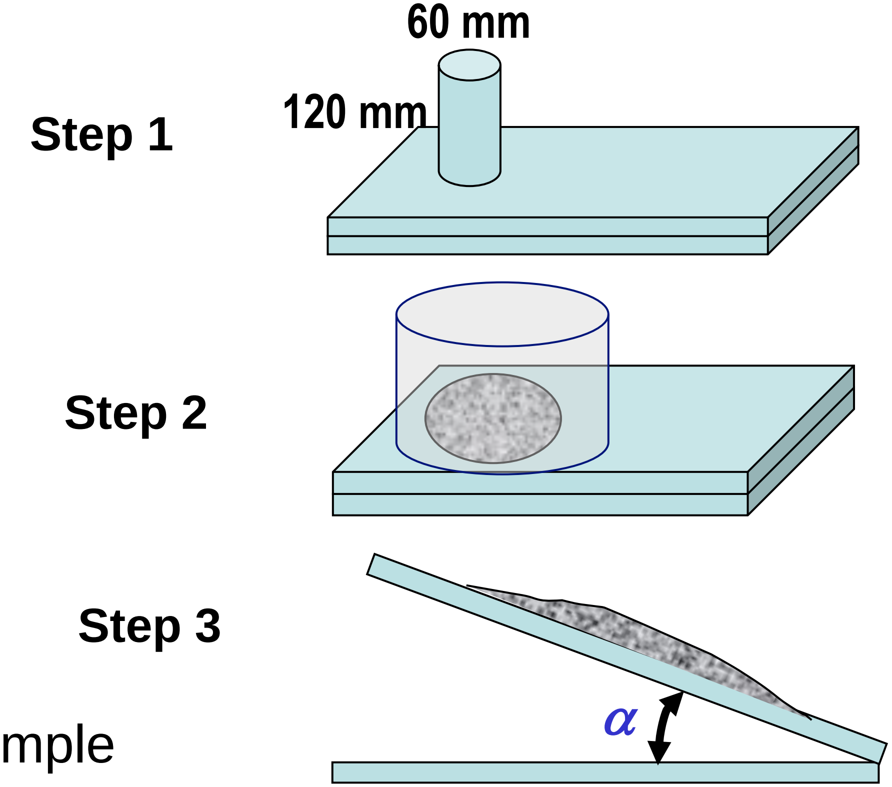
Slump flow 600-720 mm



Inclined plane (IP) test



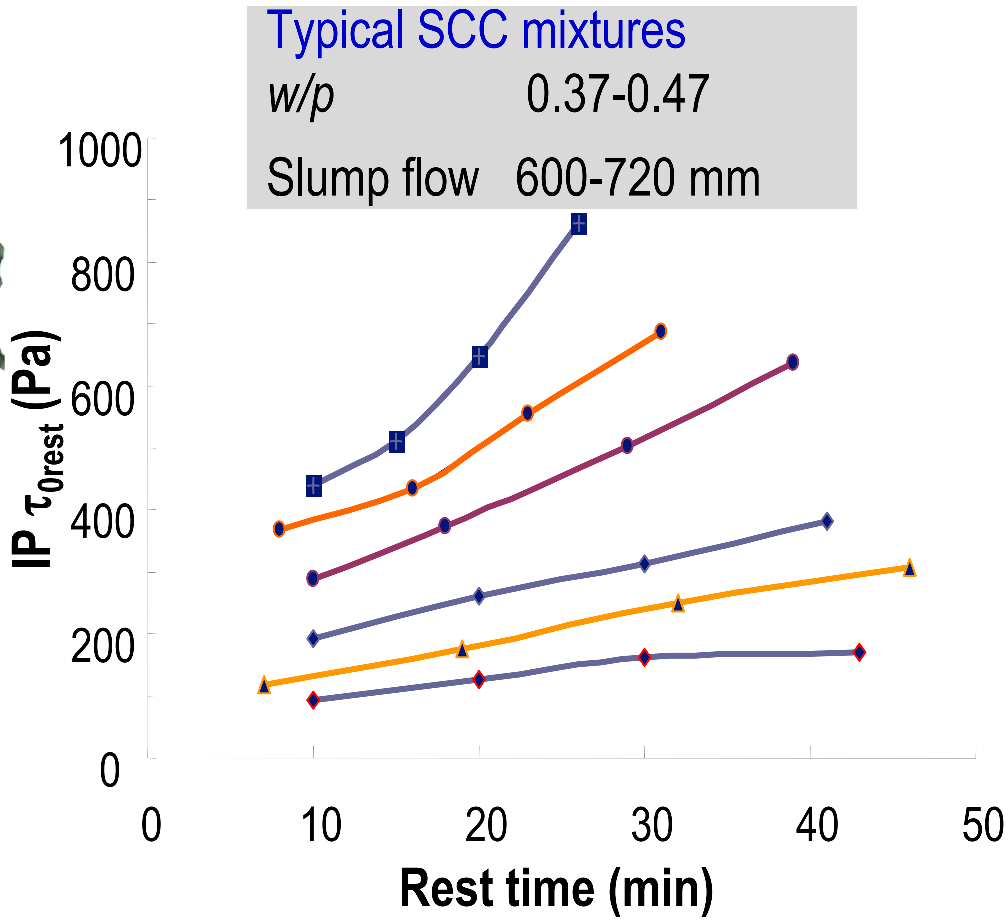
Motion takes place in the form of planer fluid layers gliding over each others in the direction of the slope



$$\tau_s = \rho g h \sin\alpha$$

ρ = density of sample
g = gravitation constant
h = mean central height of slumped sample
α = critical angle of plane at flow start

Inclined plane (IP) test



Typical SCC mixtures

w/p 0.37-0.47

Slump flow 600-720 mm

$$IP\tau_{0rest} = \rho g h \sin\alpha$$

ρ = density of sample

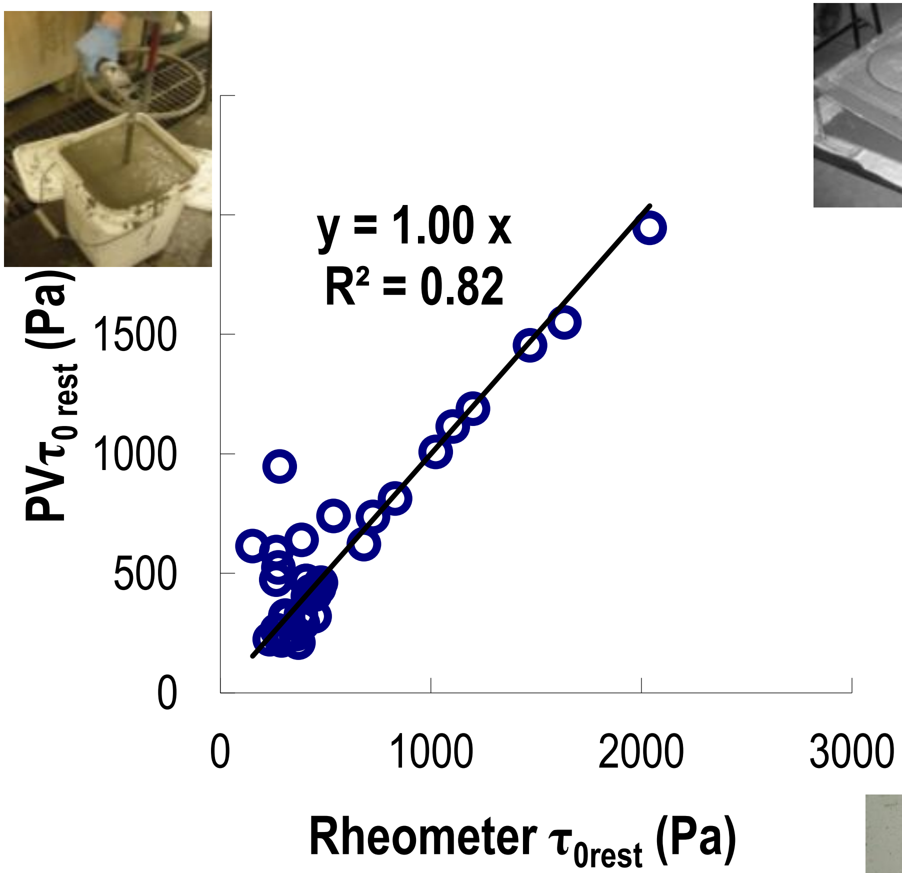
g = gravitation constant

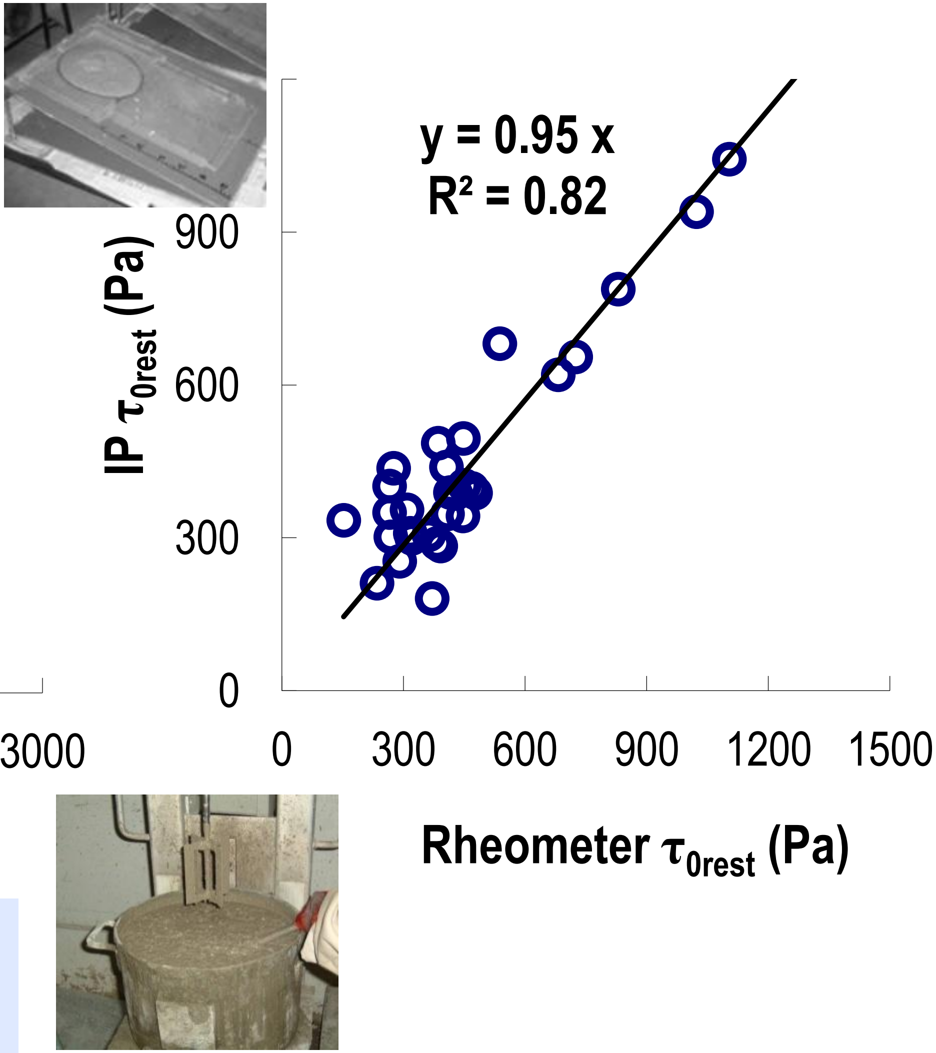
h = mean central height of slumped sample

a = critical angle of plane at flow start

Yield stress at rest: PV and IP tests vs. rheometer

Data at 15 min rest time





Good relationships between static yield stress from PV and IP vs. rheometer

Thixotropy as input to evaluate formwork pressure for SCC

$$P_{max} = \rho g H\,[a_1H + a_2R + a_3T + a_4D_{min} + a_5TI_{@fixed\ Temp.}]$$

$$P_{max} = \rho g H\,[a_1H + \xcancel{a_2R} + a_3T + a_4D_{min} + a_5TI_{@various\ Temp.}]$$

- ρ: unit weight of SCC
- H: casting depth in the form
- R: casting rate
- T: concrete temperature
- D_{min}: formwork width
- **TI**: thixotropy index: $TI_{@fixed\ temperature\ (22^{o}C)}$ or $TI_{@various\ temperature\ (ti)}$.

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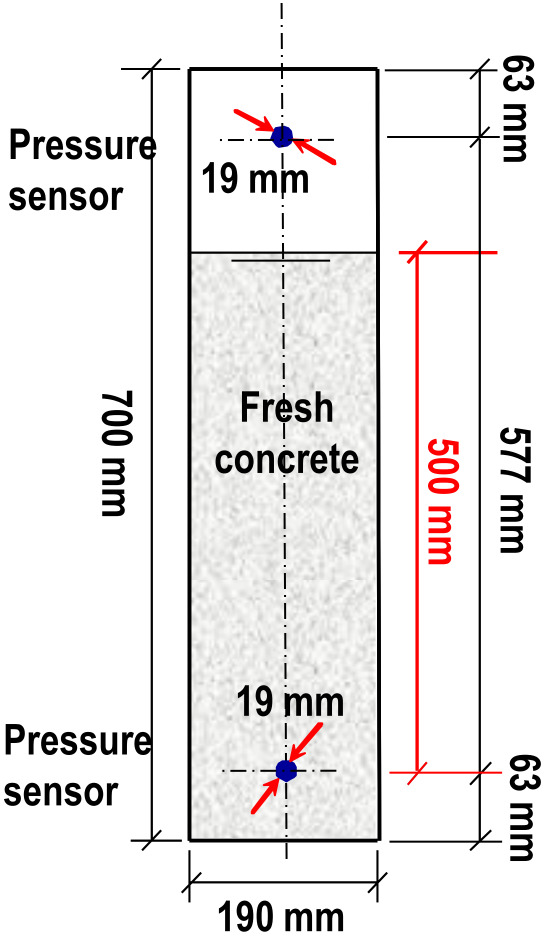
SDC Members (2007 – 2009)

Pressure device to determine lateral pressure



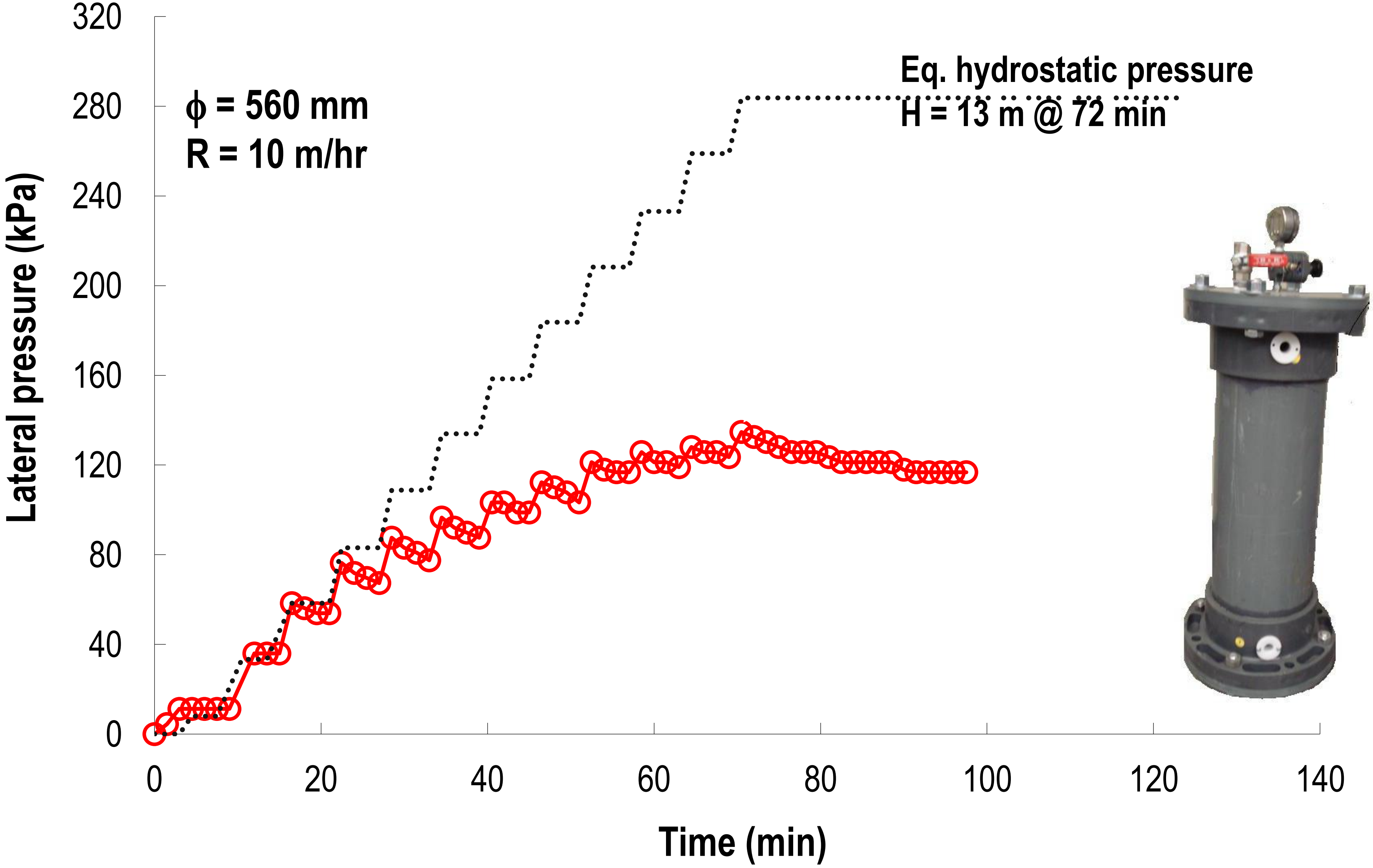
Digital manometer to control overhead air pressure

(up to 13 m high)

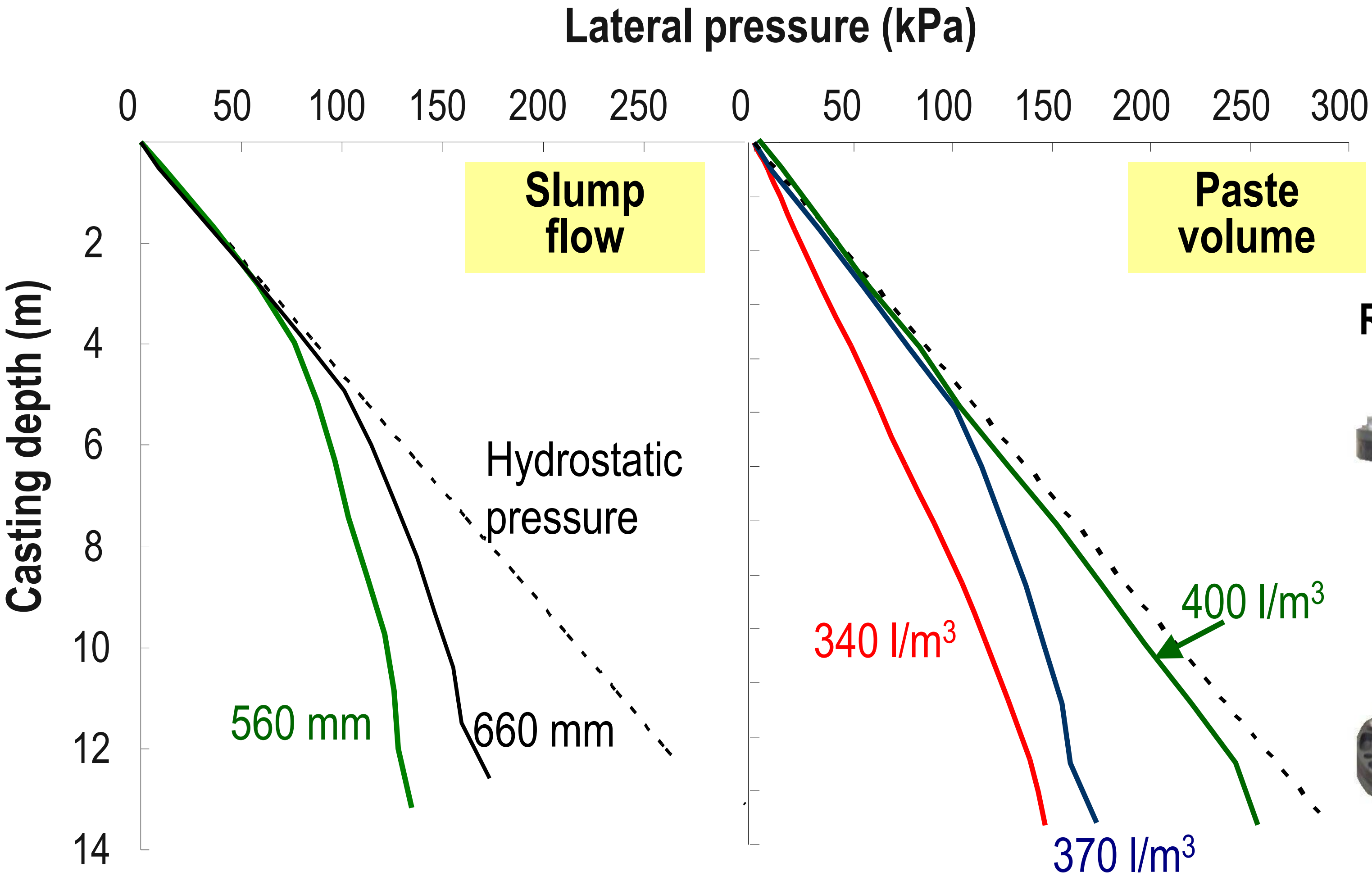
Honeywell pressure sensor

(1400-kPa capacity)

Pressure variations



Use of pressure device to validate mix design



R = 10 m/hr

Empirical models for $K_0 = f\,(H, R, T, D_{min}, PV_{thixo\ index})$

800 data points to derive models

NCSS, 2007 software

H = 1 - 13 m

R = 2 - 30 m/h

T = 10 - 32 ºC

γ_c = unit weight (e.g. 23.5 kN/m^3)

d = min. formwork dimension (0.2 – 1.0 m)

D_{min} = Equivalent to ***d***

For 0.2 < ***d*** < 0.5 m, D_{min} = ***d***

For 0.5 < ***d*** < 1.0 m, D_{min} = 0.5 m

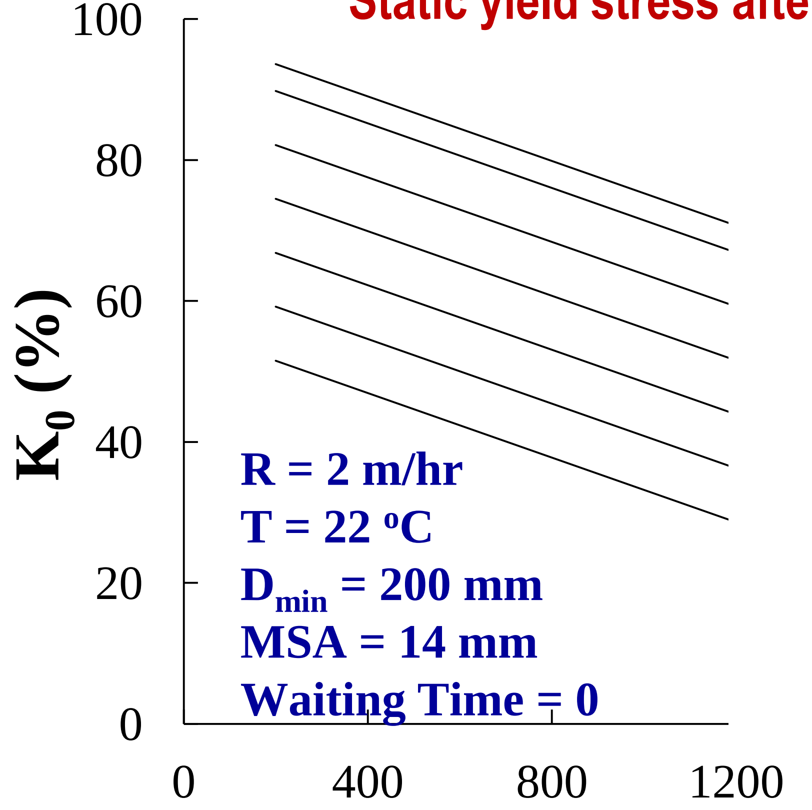
$$P_{max} = \frac{\gamma_c H}{100}\left(112.5 - 3.8\,H + 0.6\,R - 0.6\,T + 10\,D_{min} - 0.021\,PV\tau_{0rest@15\,min}\right) f_{MSA} \times f_{WT}$$

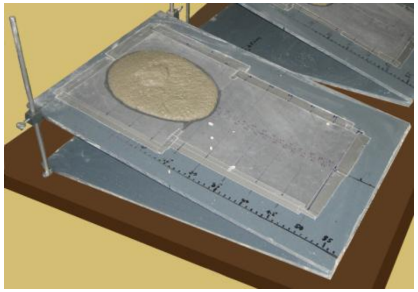
$$P_{max} = \frac{\gamma_c H}{100}\left(109.5 - 3.9\,H + 0.7\,R - 0.6\,T + 3\,D_{min} - 0.29\,PV\tau_{0rest}(t)\right) f_{MSA} \times f_{WT}$$

$$P_{max} = \frac{\gamma_c H}{100}\left(106 - 4\,H + 0.6\,R - 0.63\,T + 10\,D_{min} - 0.00015\,PV\tau_{0rest@15min} \times PV\tau_{0rest}(t)\right) f_{MSA} \times f_{WT}$$

Empirical models for $K_0 = f\,(H, R, T, D_{min}, IP_{thixo\ index})$

Static yield stress after 15 min of rest [R_i] (Pa)



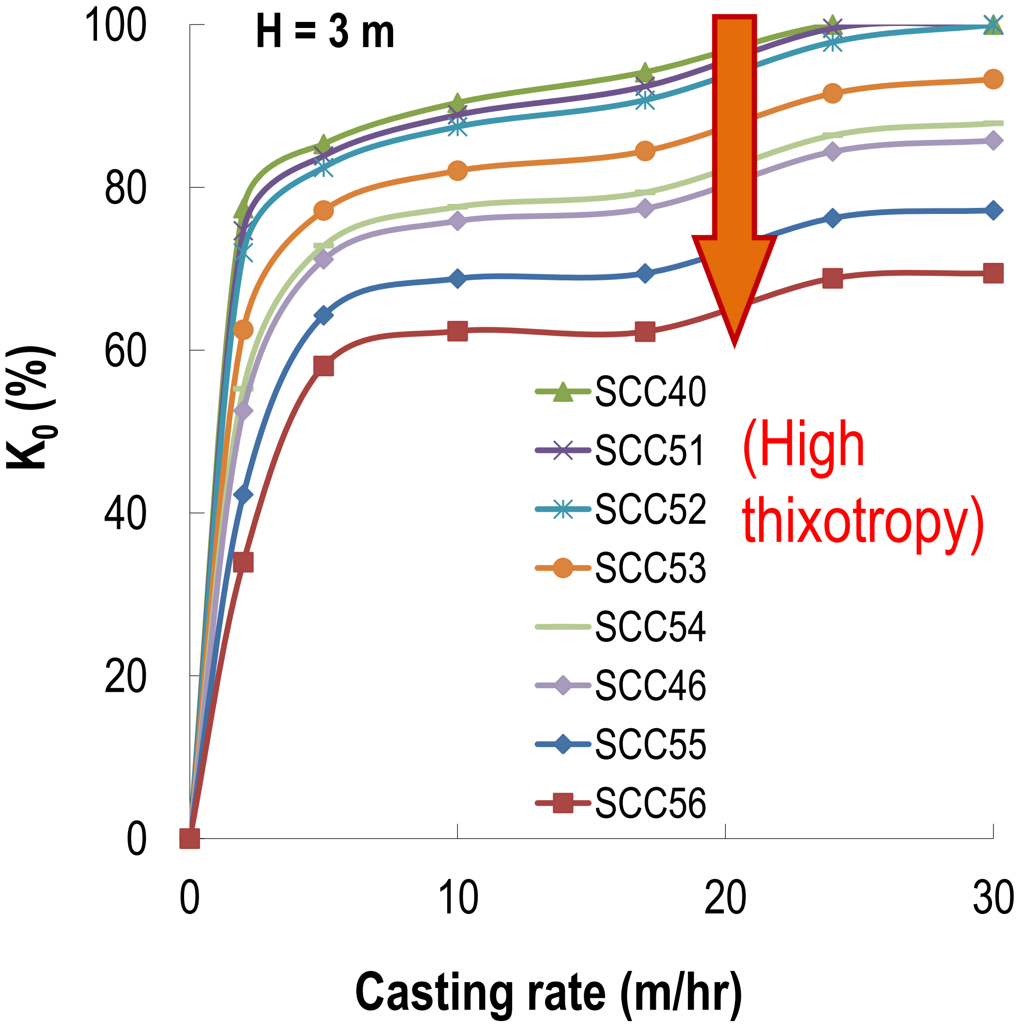


$$K_0 = [112 - 3.83\,H + 0.6R - 0.6T + 0.01D_{min} - 0.023\,IP\tau_{0rest@15min}] \times f_{MSA} \times f_{WT}$$

Effect of casting rate on lateral pressure characteristics

Pressure can be reduced by:

lowering casting speed, or increasing thixotropy



Charts for relative lateral pressure K_0

PV$\tau_{0rest@15min}$ = 200 Pa

R (m/hr)

H (m)	1	2	5	10	15	20	25	30
0	0	0	0	0	0	0	0	0
1	22	22	22	23	23	24	25	26
2	41	42	42	44	45	47	48	49
3	59	60	61	63	65	67	69	71
4	76	76	78	81	83	86	89	92
5	90	91	93	96	100	103	107	110
6	103	104	106	110	114	119	123	127
7	114	115	118	123	127	132	137	142
8	123	124	128	133	139	144	150	155
9	131	132	136	142	148	154	161	167
10	136	138	142	149	156	163	170	177
11	140	142	147	154	162	169	177	185
12	143	144	151	158	166	174	183	191
13	143	145	154	159	168	177	186	195

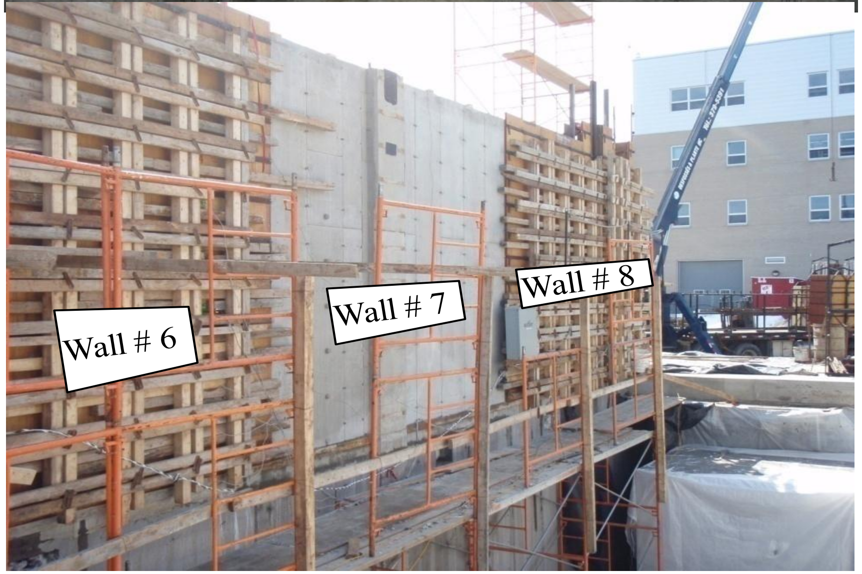
- < 50 kPa
- 50- 80 kPa
- 80 - 110 kPa
- 110 - 140 kPa
- 140 - 170 kPa
- >170 kPa

PV$\tau_{0rest@15min}$ = 1200 Pa

R (m/hr)

H (m)	1	2	5	10	15	20	25	30
0	0	0	0	0	0	0	0	0
1	17	17	17	18	19	19	20	21
2	32	32	33	34	35	37	38	40
3	45	45	46	49	51	53	55	57
4	56	57	58	61	64	67	70	72
5	66	67	69	72	76	79	82	86
6	74	75	77	81	85	90	94	98
7	80	81	84	89	94	98	103	108
8	84	86	89	94	100	105	111	117
9	87	88	92	98	105	111	117	123
10	88	89	94	100	107	114	121	128
11	87	89	93	101	108	116	124	131
12	85	86	93	100	108	116	124	133
13	80	82	91	96	105	114	123	132

Integrated research laboratory on materials valorization and innovative and durable structures - 2007-2009



Formwork

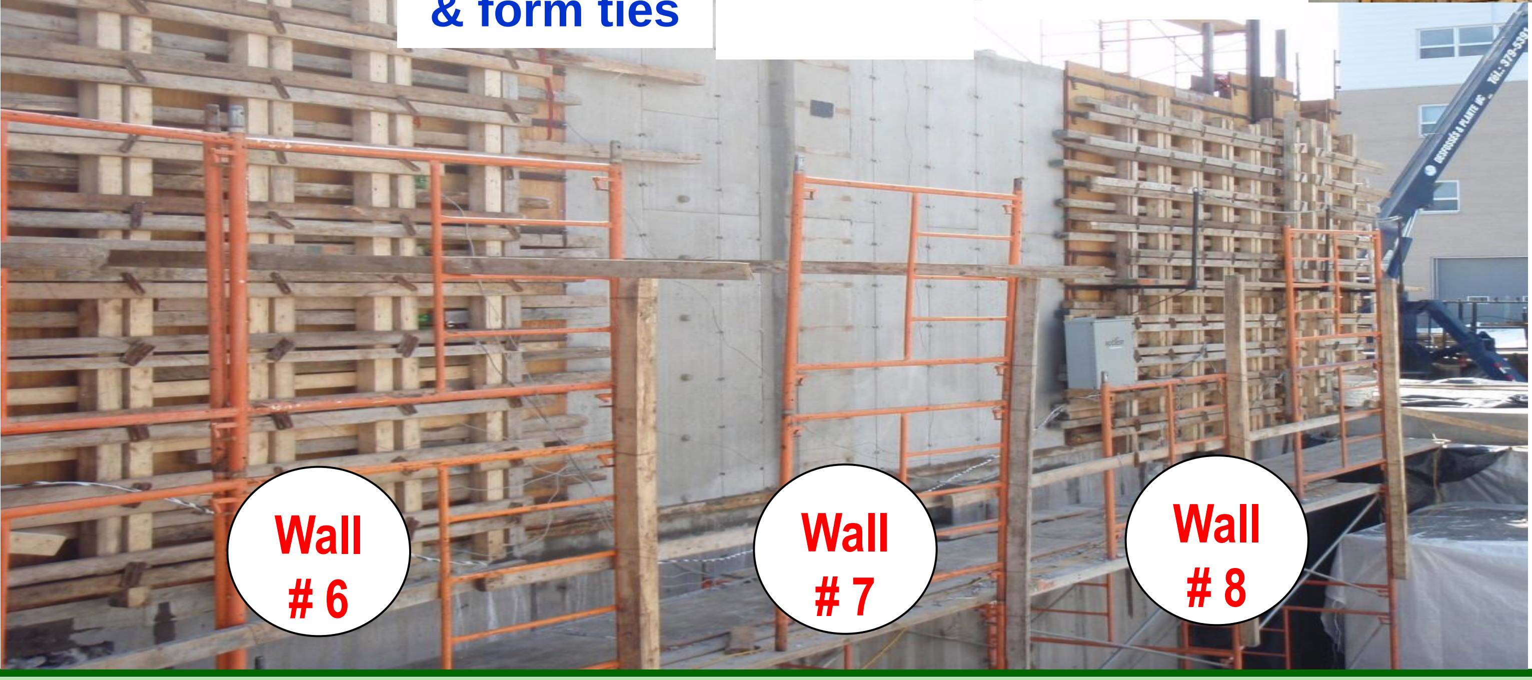
16 mm bars
@ 30 x 40 cm

Sheathing
& form ties

Snap
form ties

Tie clamps

Wall
studs &
Wales



2 walls/day

Investigated parameters

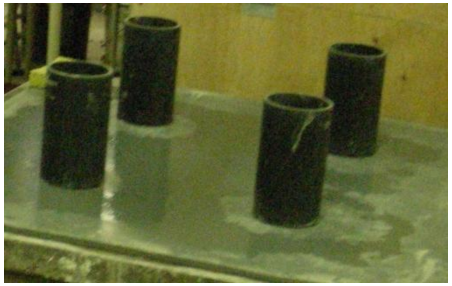
	Level 1000, H = 3.7 m (effect of casting rate)				Level 2000, H = 4.4 m (effect of thixo.)			
	Wall #1 VCC	Wall #2 SCC1	Wall #3 SCC1	Wall #4 SCC1	Wall #5 VCC	Wall #6 SCC1	Wall #7 SCC2	Wall #8 SCC3
Slump/ slump flow (mm)	120 ± 30	650 ± 25			120 ± 30	650 ± 25		
HRWRA type	---	PCP			---	PCP		PNS
Vp (L/m^3)	---	Low, 330			---	Low 330	High 370	Low 330
R (m/hr)	7.5	5	10	15	7.5	10		
W/CM	0.40	0.35			0.40	0.37	0.35	0.42+VMA

Air content < 3.5%, concrete temp. = 22 – 25 °C

Full characterization

10 persons to carry out > 17 tests

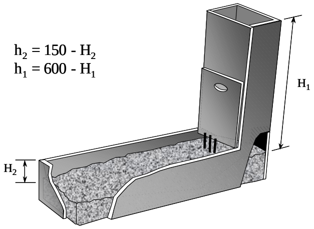






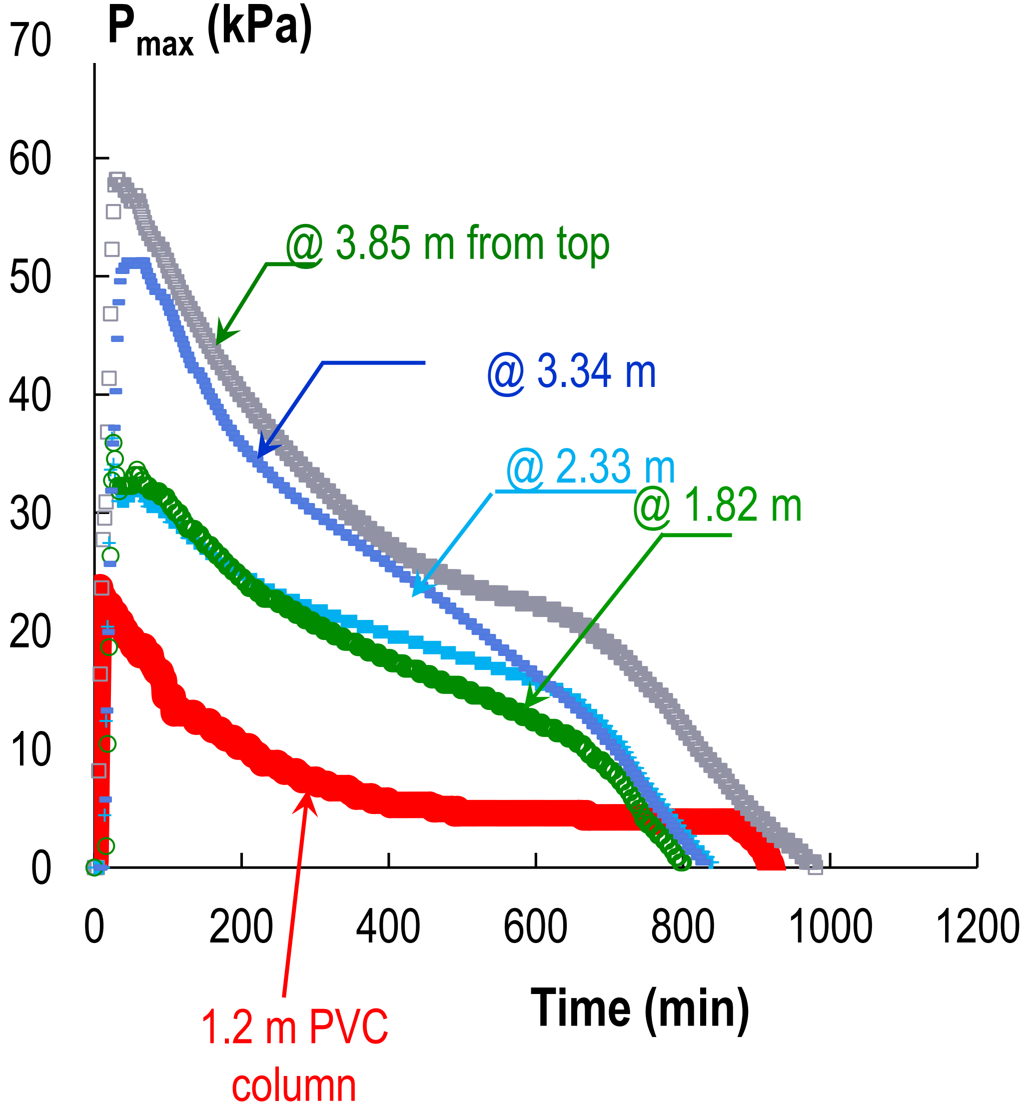


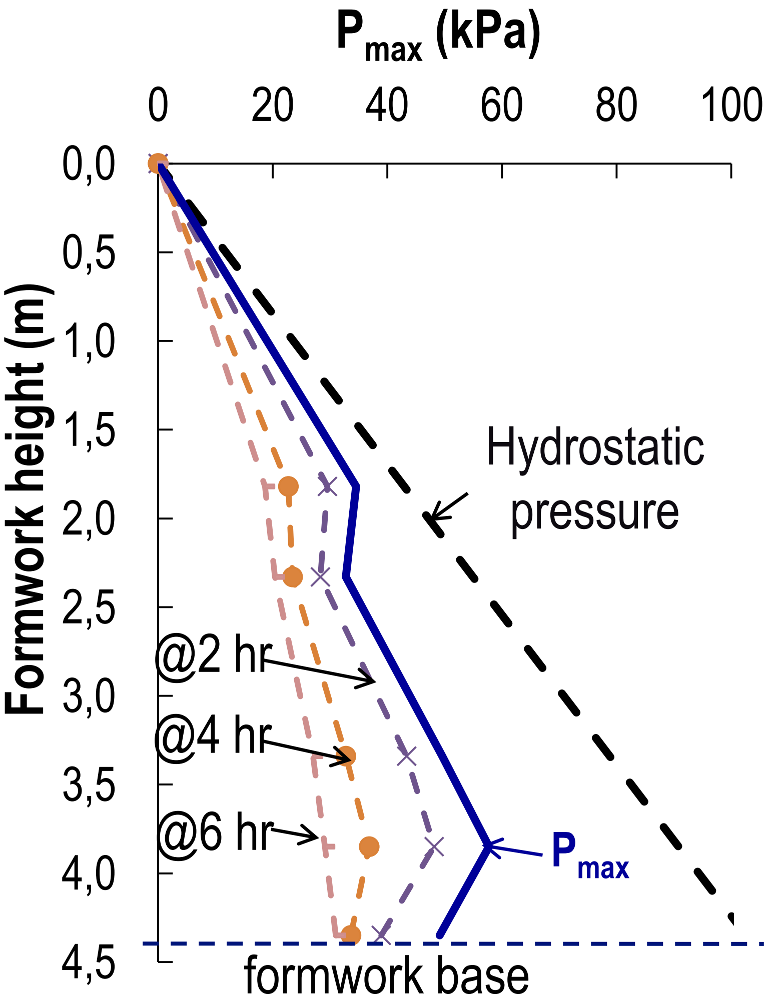



Strength

Shrinkage

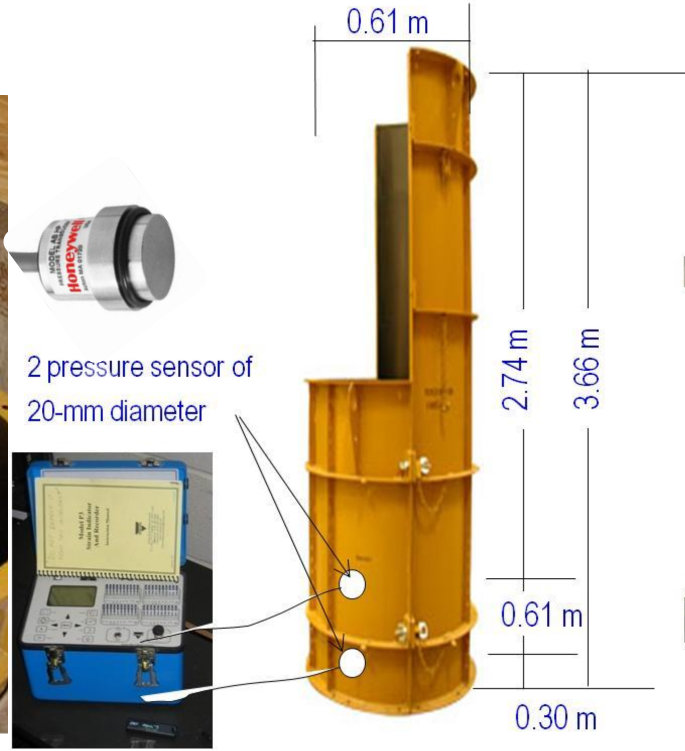
Lateral pressure [wall # 6, SCC1, R = 10 m/h]





8 full-scale R/C columns

Mixture	Relative thixotropy	Casting rate (m/h)						
		2	5	5 + 20’ WP	10	13	15	22
SCC-L	Low	--	--	--	--	Col.#1	--	Col.#2
SCC-M	Medium	--	Col.#7	Col.#8	--			
SCC-H	High	Col.#5	Col.#3	--	Col.#4	--	Col.#6	--

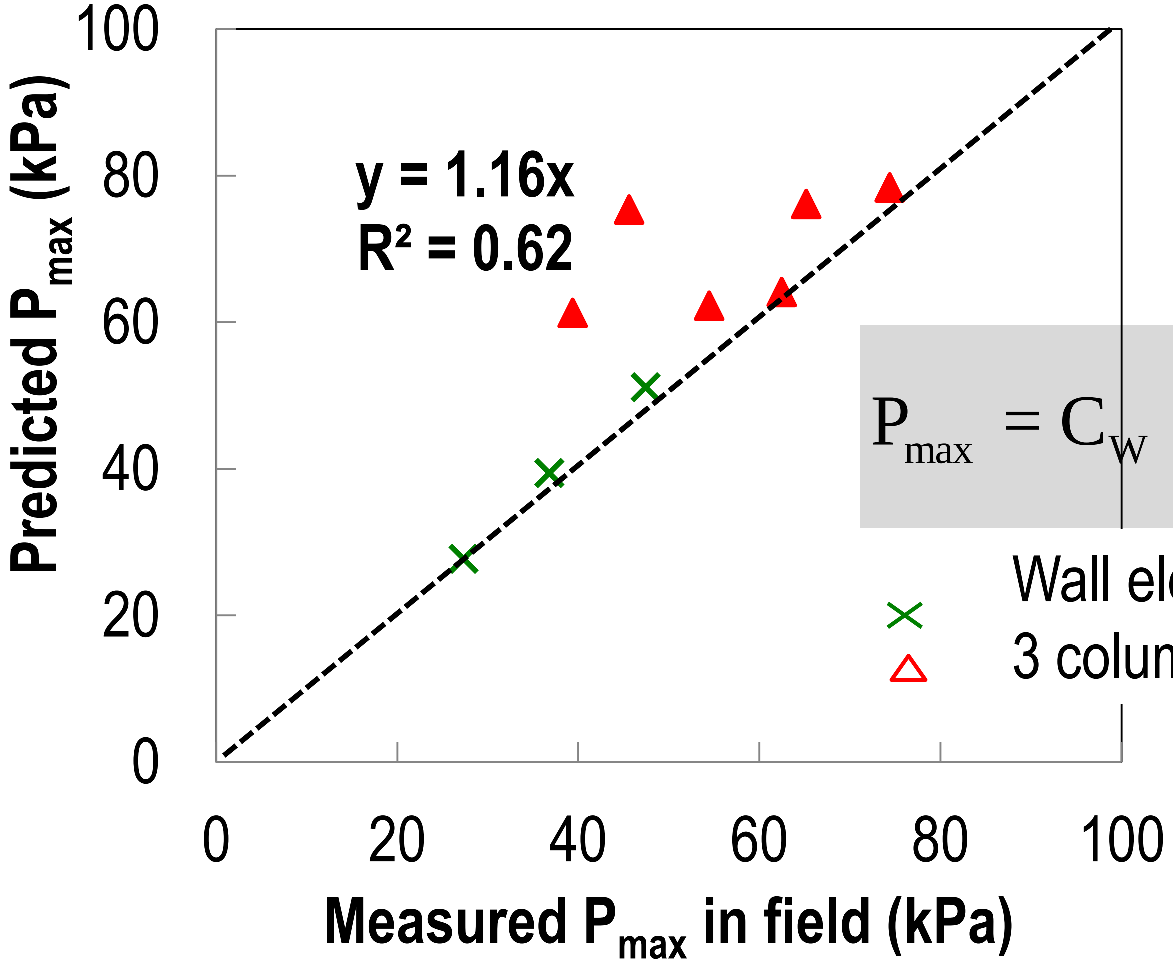


ACI 347-04 vs. field measurements

Casting rate limited to 4.5 m/h (ACI 347-04)

Walls and columns cast of ≤ 5 m/h are considered

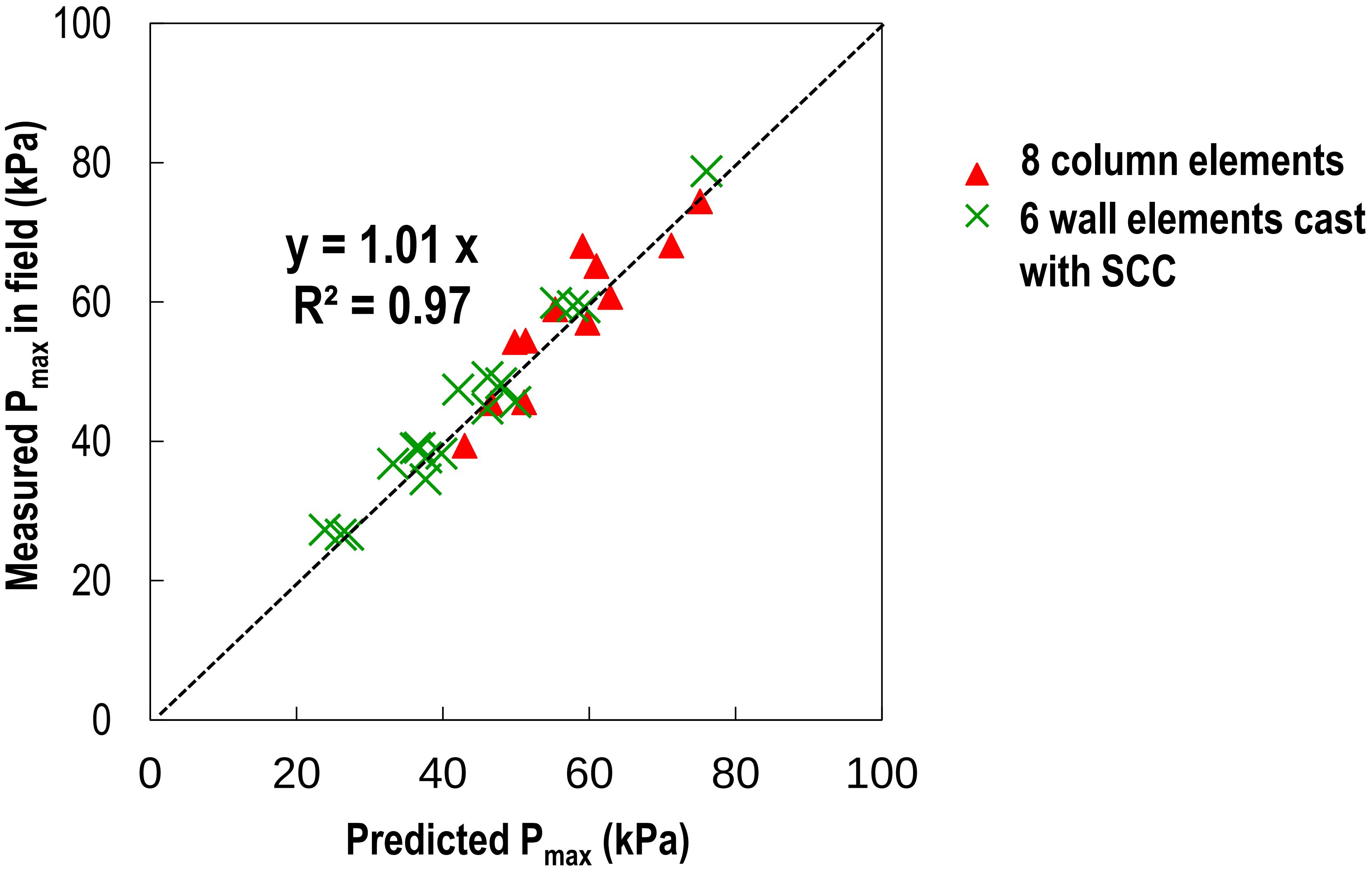
Limited data



$$P_{max} = C_W \, C_C \left(7.19 + \frac{785R}{17.78 + T} \right)$$

C_c : Chemistry coefficient = 1.2

Khayat & Omran [2009] vs. field measurements



Round-Robin Tests for prediction of form pressure (May 2012)

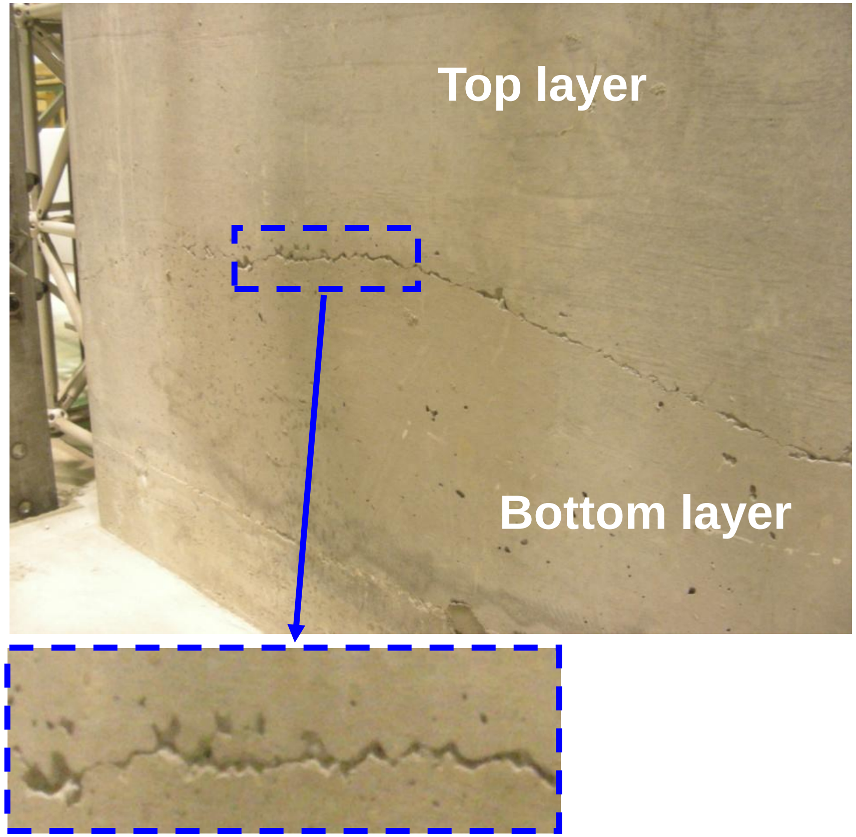
Member	Special property to be measured
T. Proske, Germany	Setting time
M. Beitzel, Germany	Structural build up / BT2
N. Roussel, France	Structural build up / Plate test
K. Khayat, USA	Structural build up / Inclined plane, Portable Vane
A. Omran, Canada	Pressure column
D. Lange, USA	Pressure decay
J. Gardner, Canada	Slump loss
Y. Vanhove, France	Friction stress / Tribometer

Outline

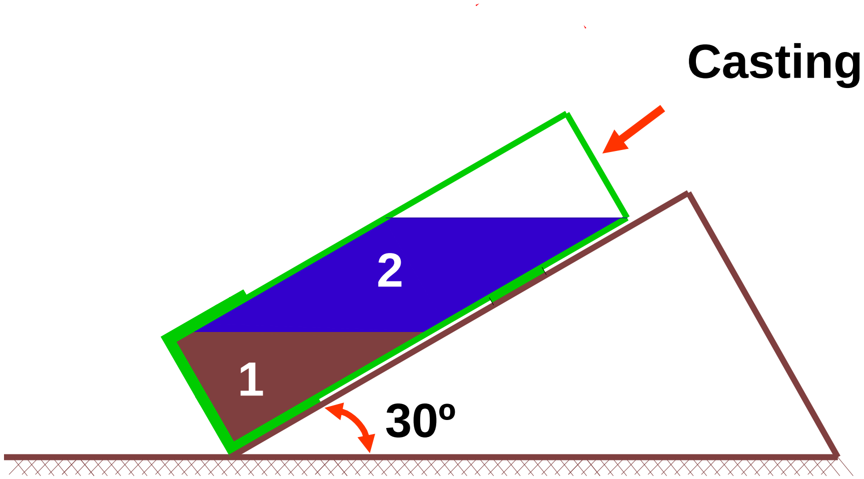
- Thixotropy determination: structural breakdown and structural build-up at rest
- Thixotropy vs. form pressure exerted by SCC
- Structural build-up vs. drop in interlayer bond

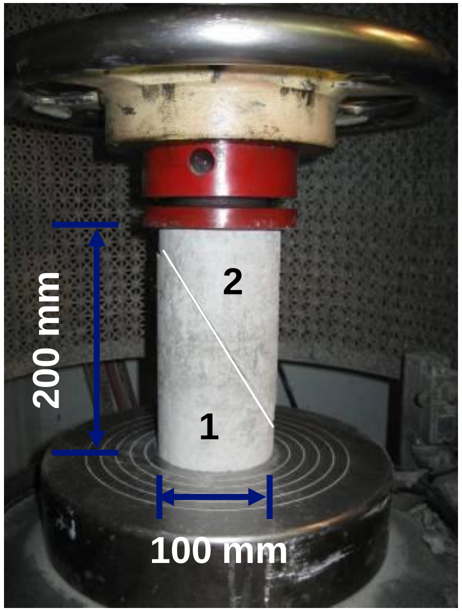
Structural build-up can lead to aesthetic problems in terms of casting folds in multi-layer placements

(U de Sherbrooke, 1997)

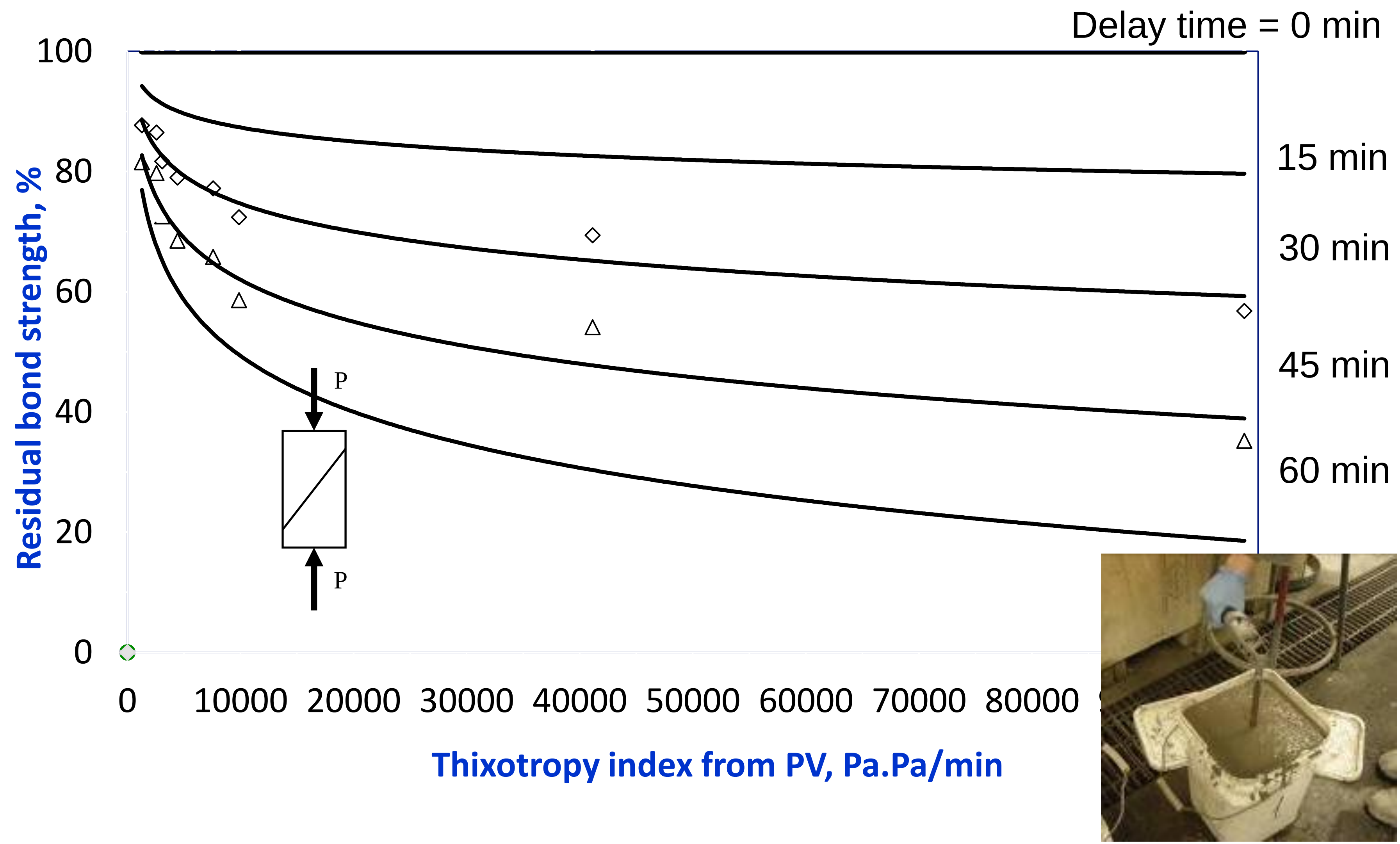


Interlayer bond strength (slanted shear strength)





Variation of residual bond strength with thixotropy and delay time between successive lifts

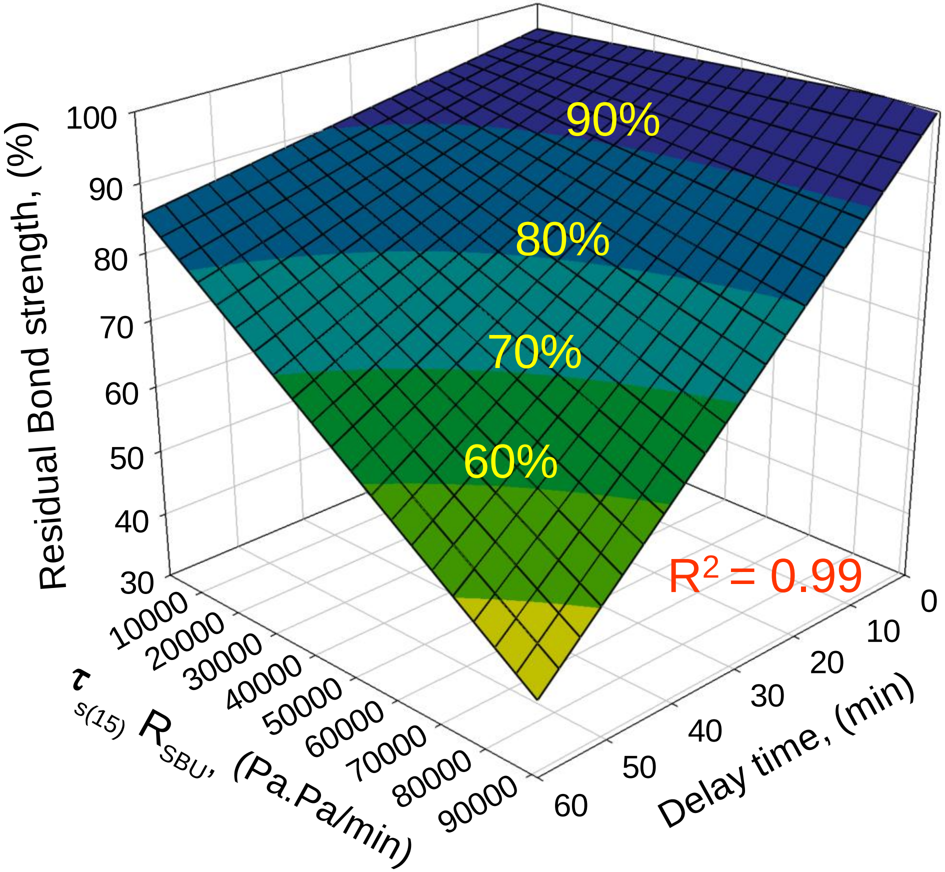


Statistical model

$$RB_{SSh}\% = -0.1608\, DT \;\; \mathrm{Ln}\, Athix2_{PV} \; +1.0922\, DT \; +100$$

RBS = Residual bond strength

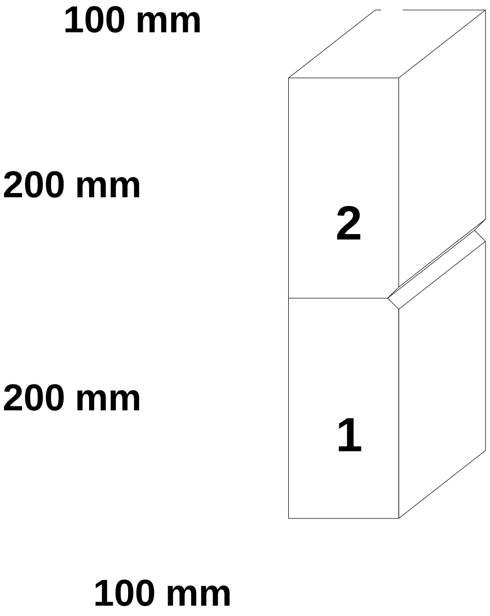
DT = Delay time between 2 layers



Residual bond strength

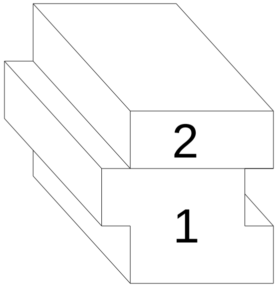
Flexural stress

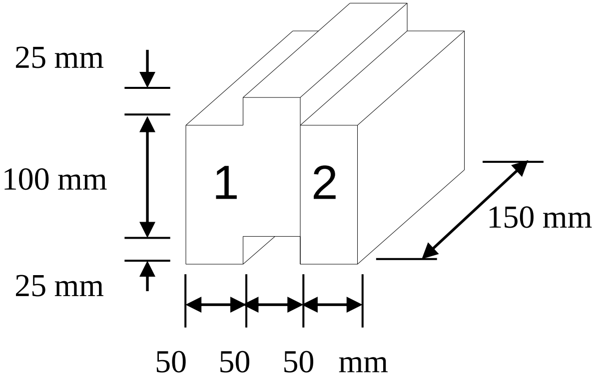
Casting point

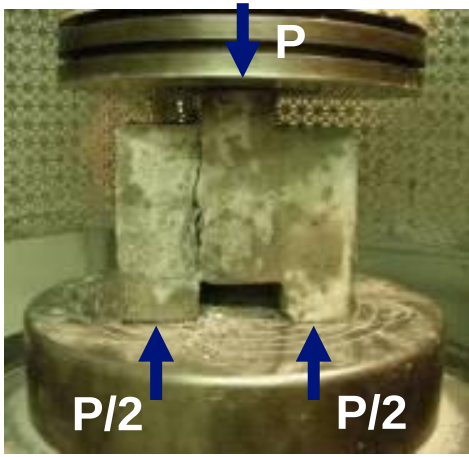


Direct shear stress

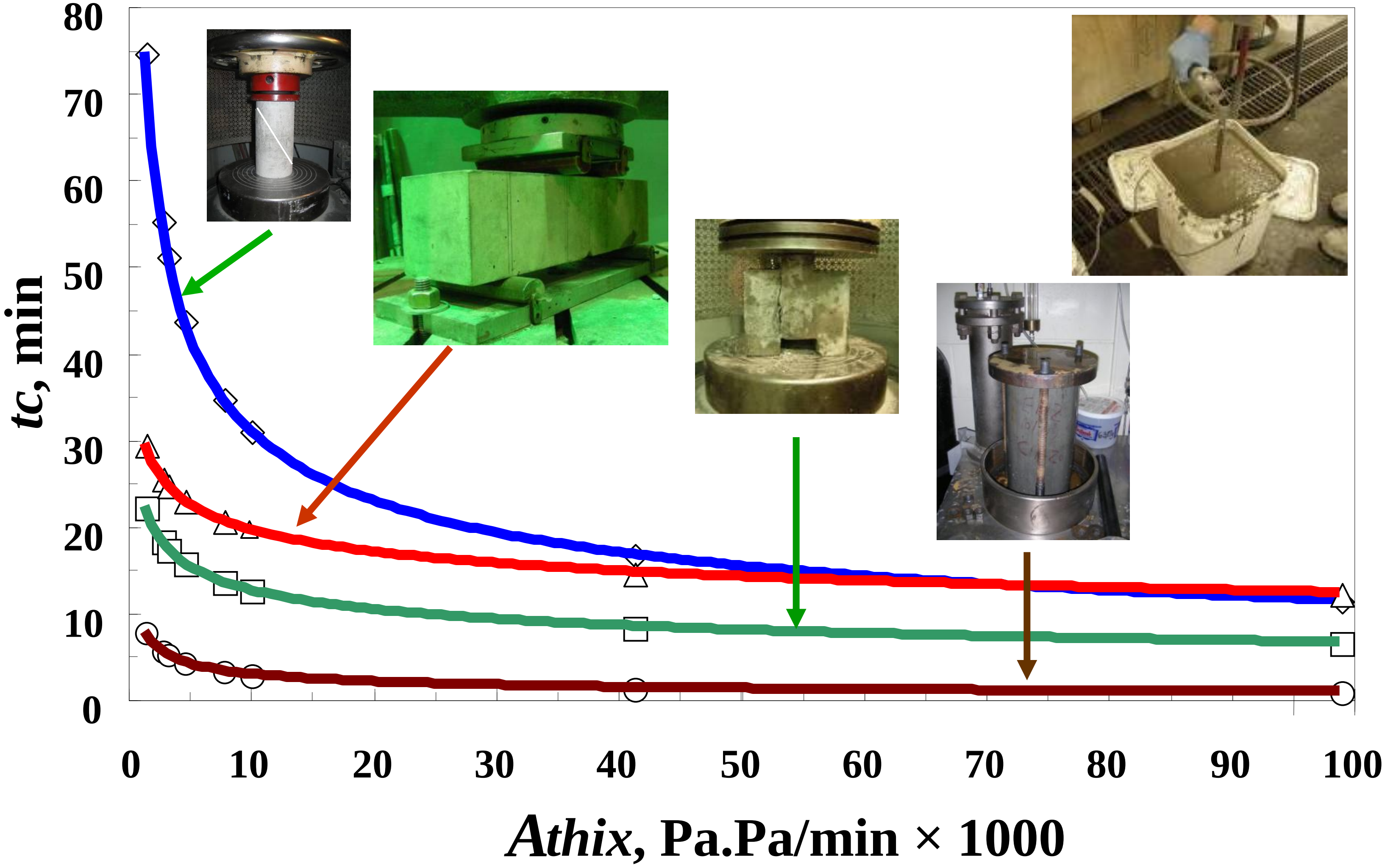
Casting point







Critical delay time to reach 90% residual bond strength



Conclusions

- Thixotropy of SCC can be assessed by structural breakdown and structural build-up at rest
- Breakdown area (Ab) or drop in apparent viscosity to assess thixotropy are determined using concrete rheometer
- Structural build-up at rest can be determined as:
  - Variation of drop in apparent viscosity with time using concrete rheometer
  - Variation of static yield stress at rest using concrete rheometer
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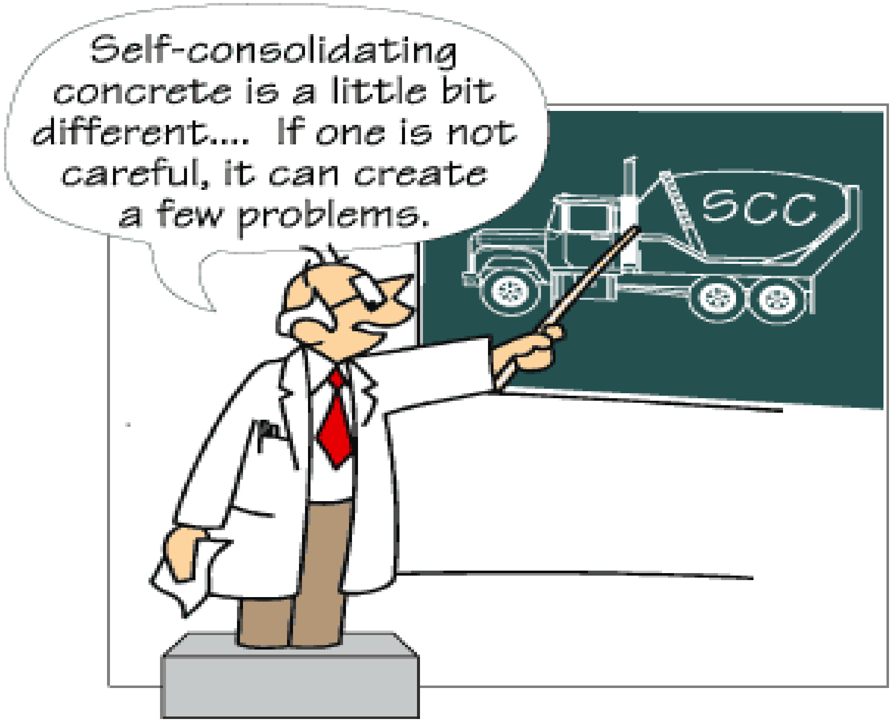
- Increase of thioxotropy leads to reduction in form pressure exerted by SCC
- Residual interlayer bond of SCC increases with decrease thixotropy (structural build-up at rest)
- Long delayed time between casting two successive SCC layers leads to reduction in interlayer bond
- Residual inter-layer bond strength is more critical in shear than in flexural or compression failure modes

Acknowledgment

NRMC Research & Education Foundation, ACI Foundation

NSERC IRC HP-Flowable Concrete with Adapted Rheology

J. Assaad, A. Omran, W. Magdi
S. Naji, P. Billberg, A. Yahia,
O. Bonneau, N. Petrov
R. Morin, M. D’Ambrosia

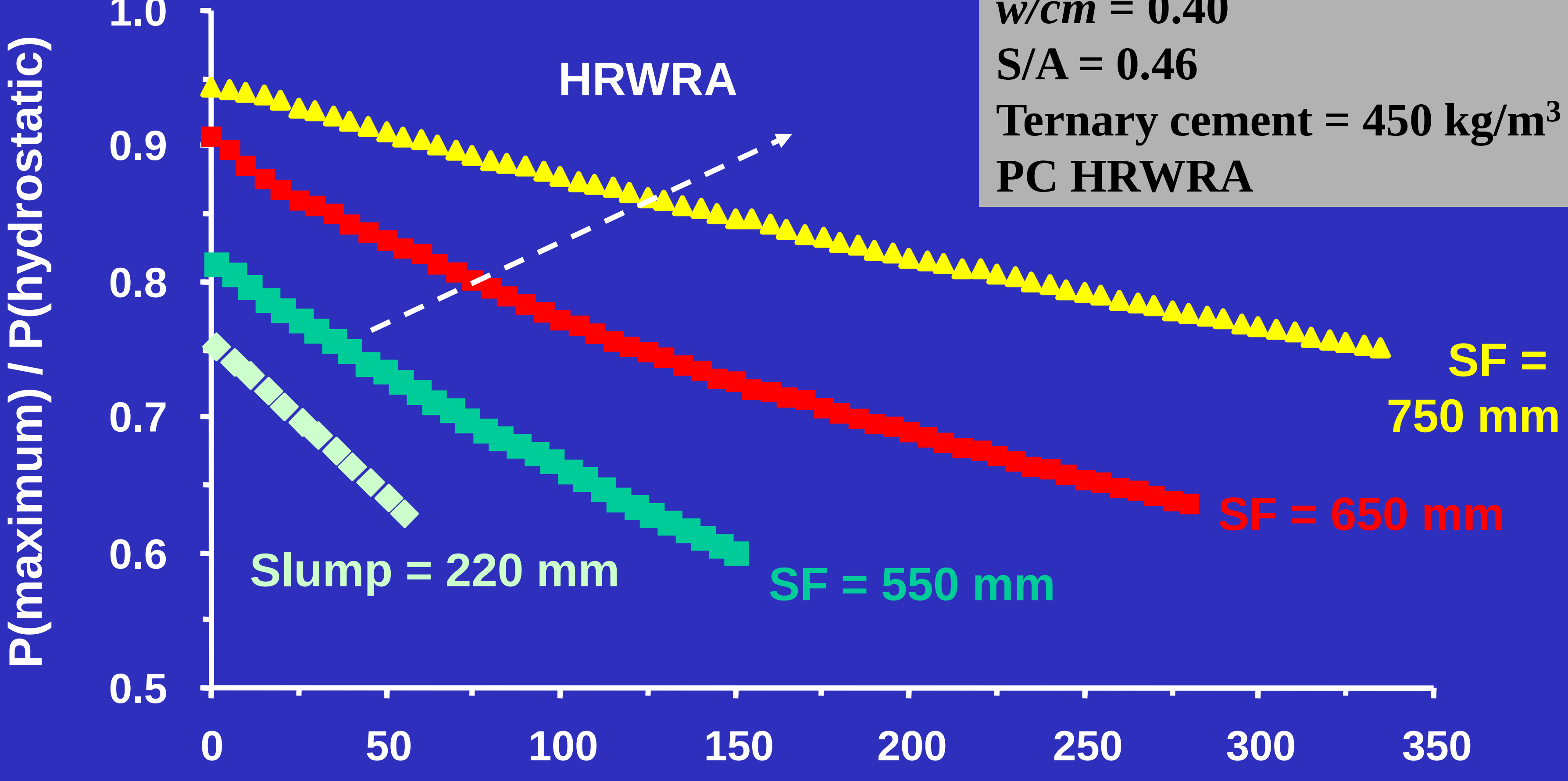


Outline

- Thixotropy determination: structural breakdown and structural build-up at rest
- Thixotropy vs. form pressure exerted by SCC
- Structural build-up vs. drop in interlayer bond
- Mixture parameters affecting thixotropy (form pressure) of SCC

Effect of Consistency Level

Slump flow = 650 mm
w/cm = 0.40
S/A = 0.46
Ternary cement = 450 kg/m^3
PC HRWRA



R = 10 m/h

Time after casting (min)

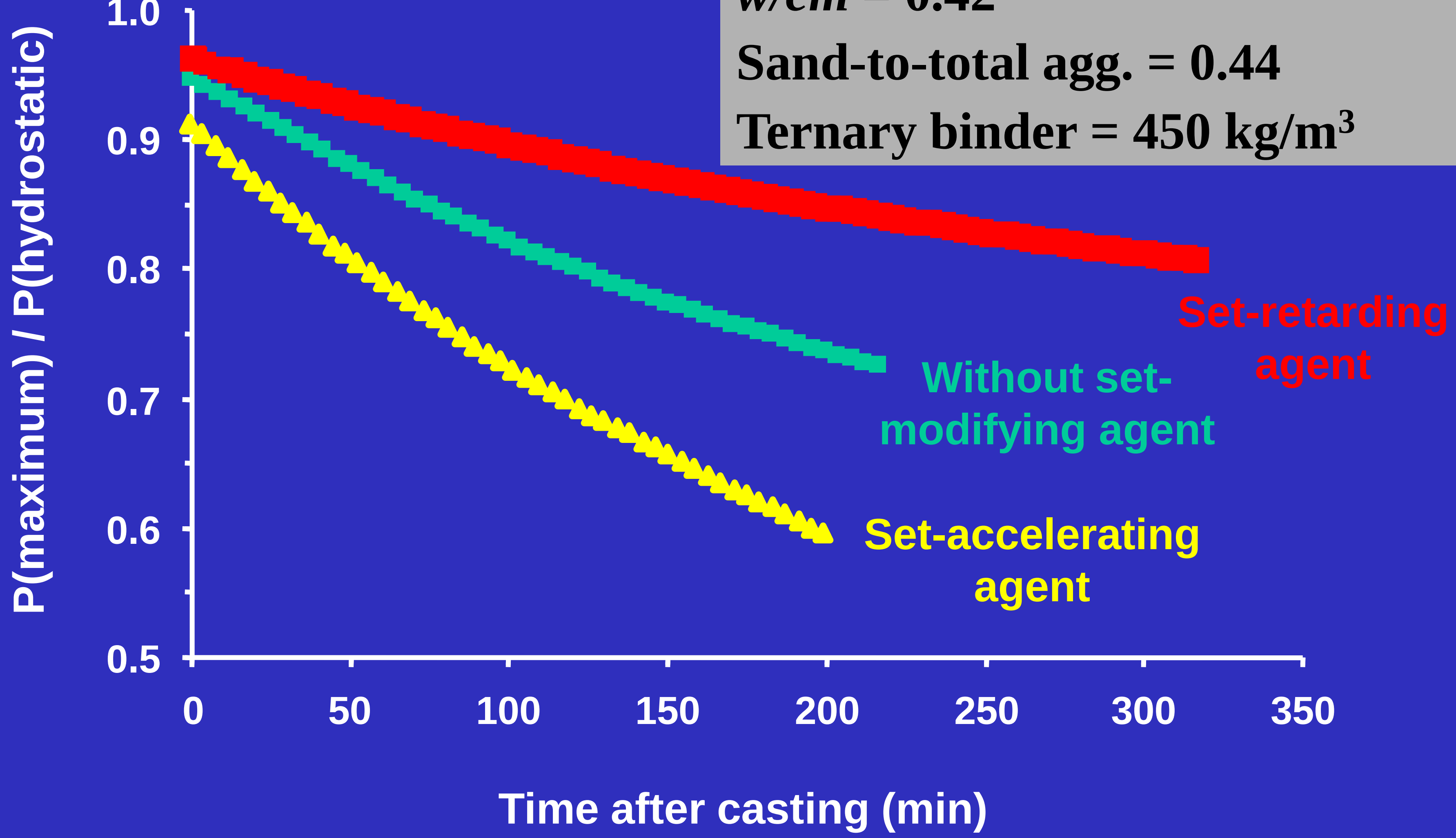
Effect of Set-Modifiers (Cohesion)

Slump flow = 650 mm

***w/cm* = 0.42**

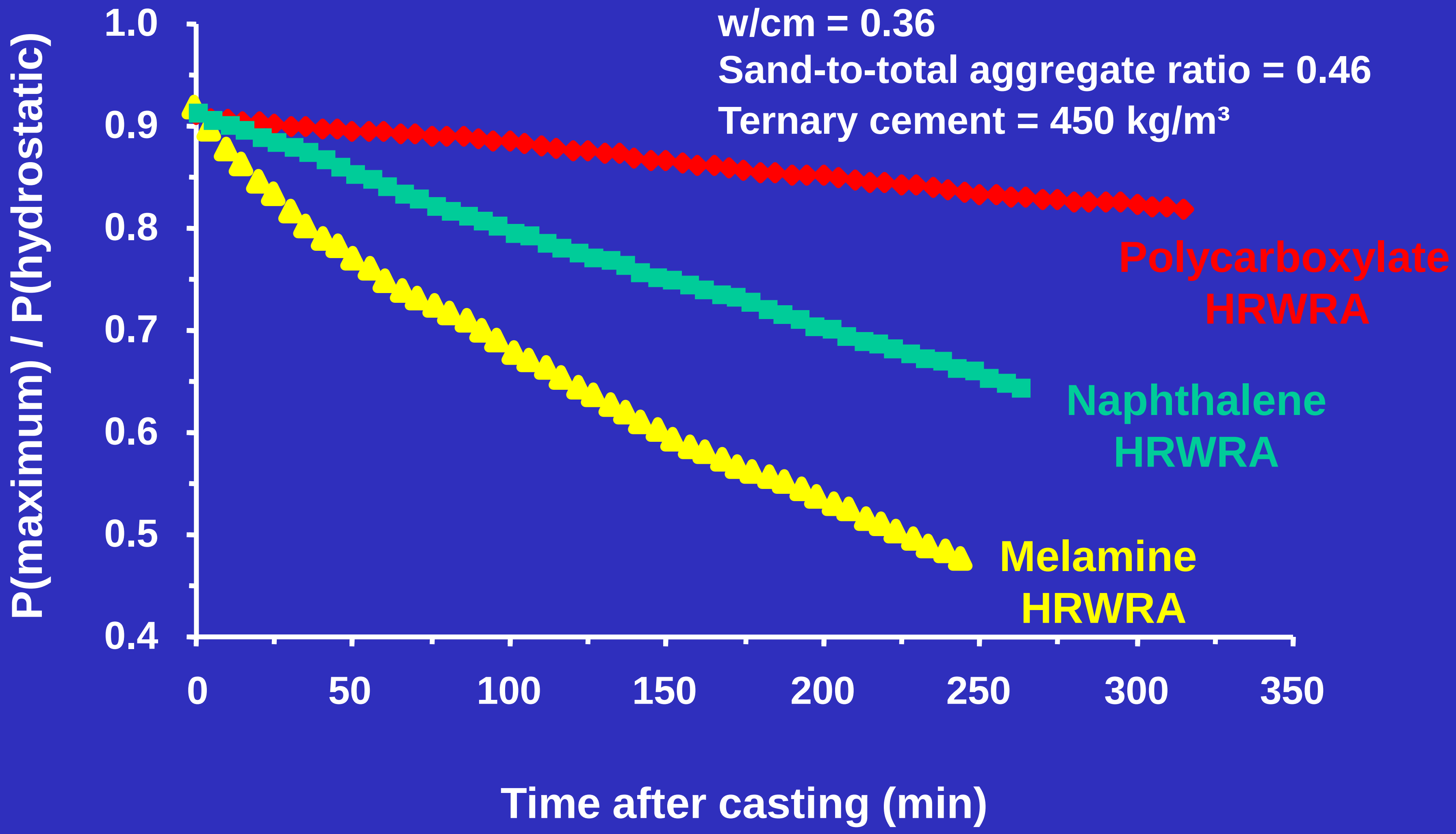
Sand-to-total agg. = 0.44

Ternary binder = 450 kg/m^3

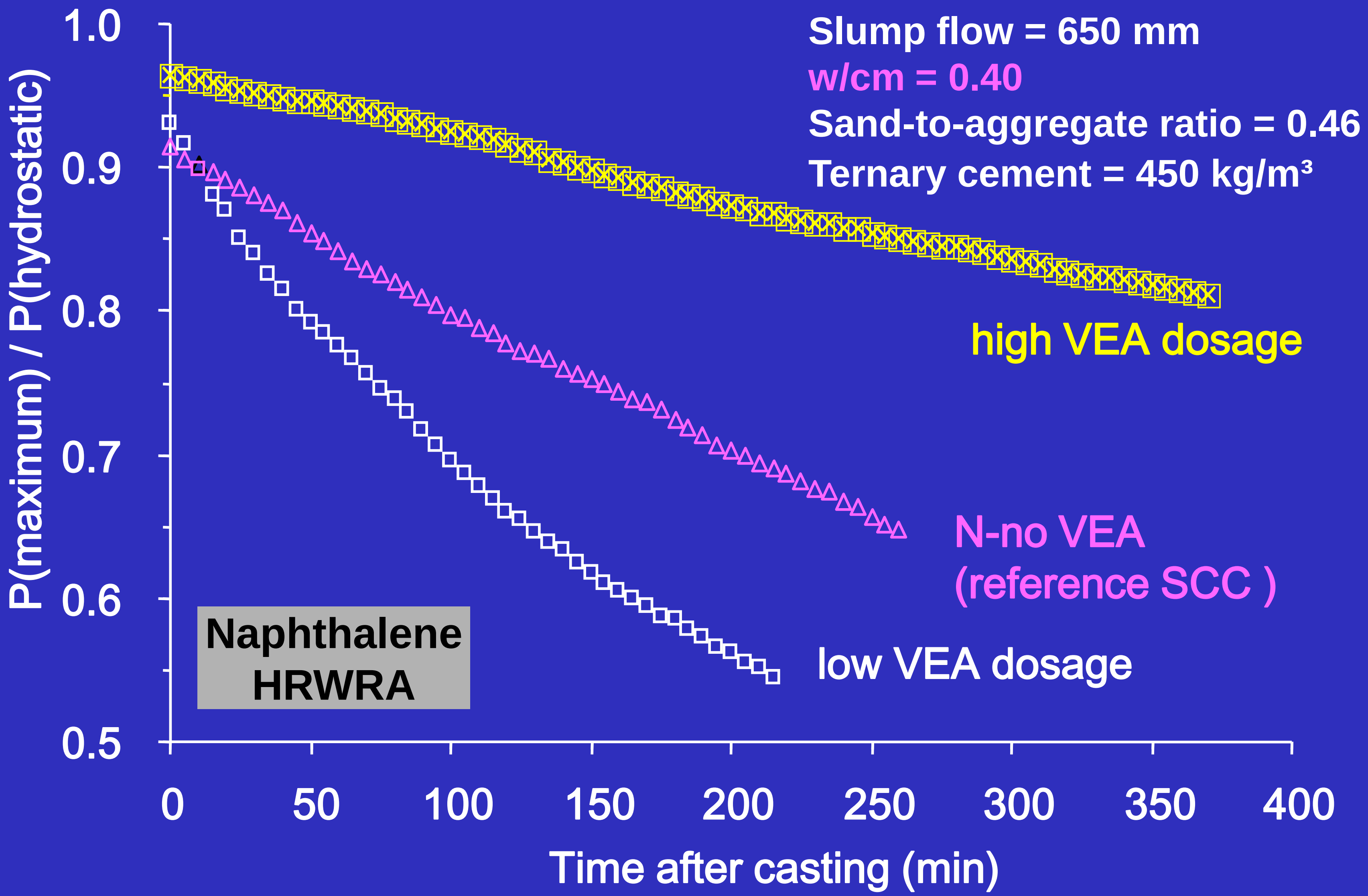


Effect of HRWRA Type

Slump flow = 650 mm
w/cm = 0.36
Sand-to-total aggregate ratio = 0.46
Ternary cement = 450 kg/m³



Effect of powder polysaccharide-based VEA content with variable SP dosages



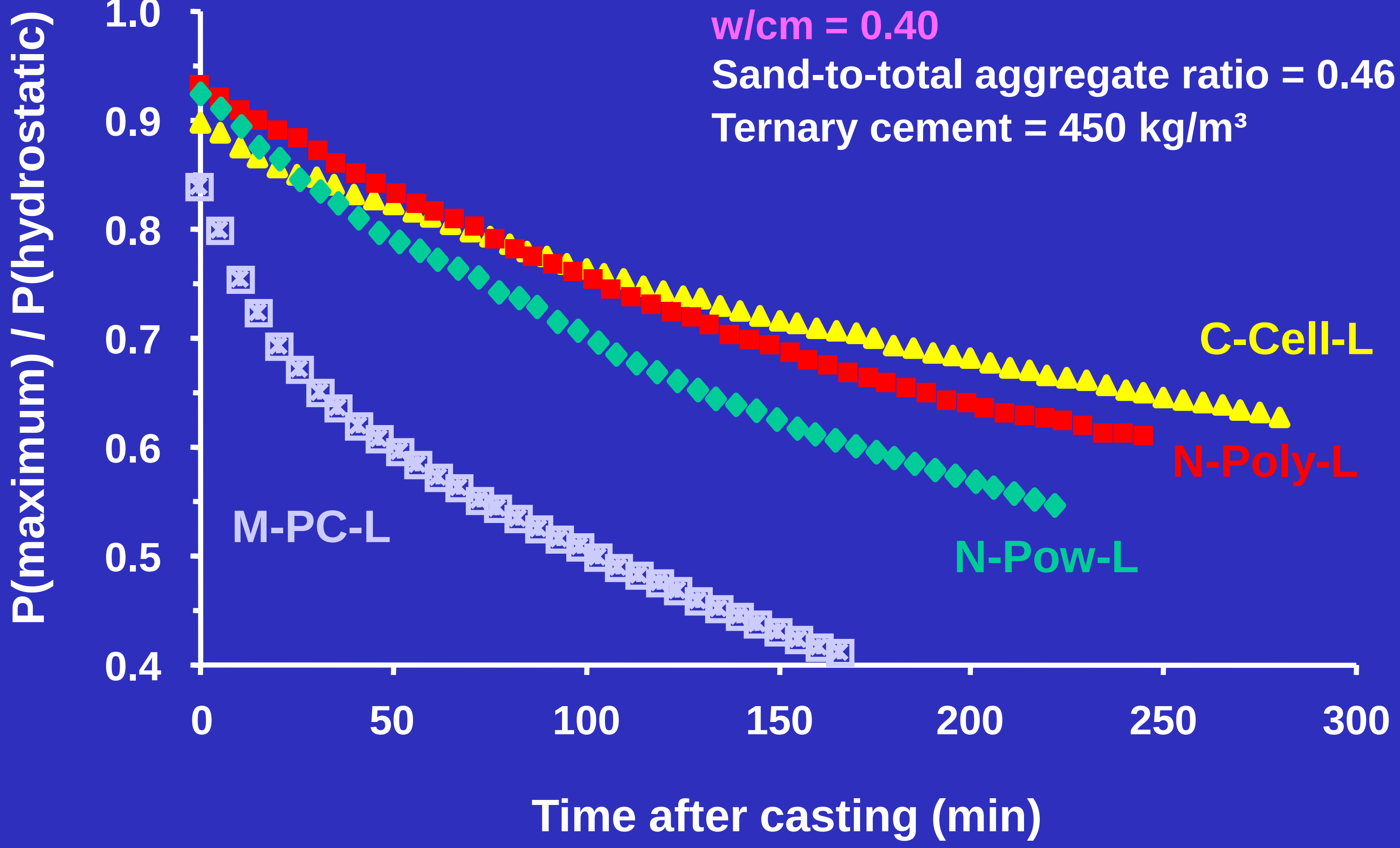
Effect of Stabilizers

Incorporation of low thickener VEA in SCC with 0.40 *w/cm* can lead to lower lateral pressure than in SCC with 0.36 *w/cm* and no VEA

Medium or high content of polysaccharide-based VEA + PNS-based HRWRA resulted in higher residual pressure and lower rate of pressure drop after casting compared to SCC with low dosage of VEA (attributed to increased HRWRA demand)

Similar results with cellulose VEA + polycarboxylate-based HRWRA

Effect of Thickner Type (low concentration)



Slump flow = 650 mm
w/cm = 0.40
Sand-to-total aggregate ratio = 0.46
Ternary cement = 450 kg/m³

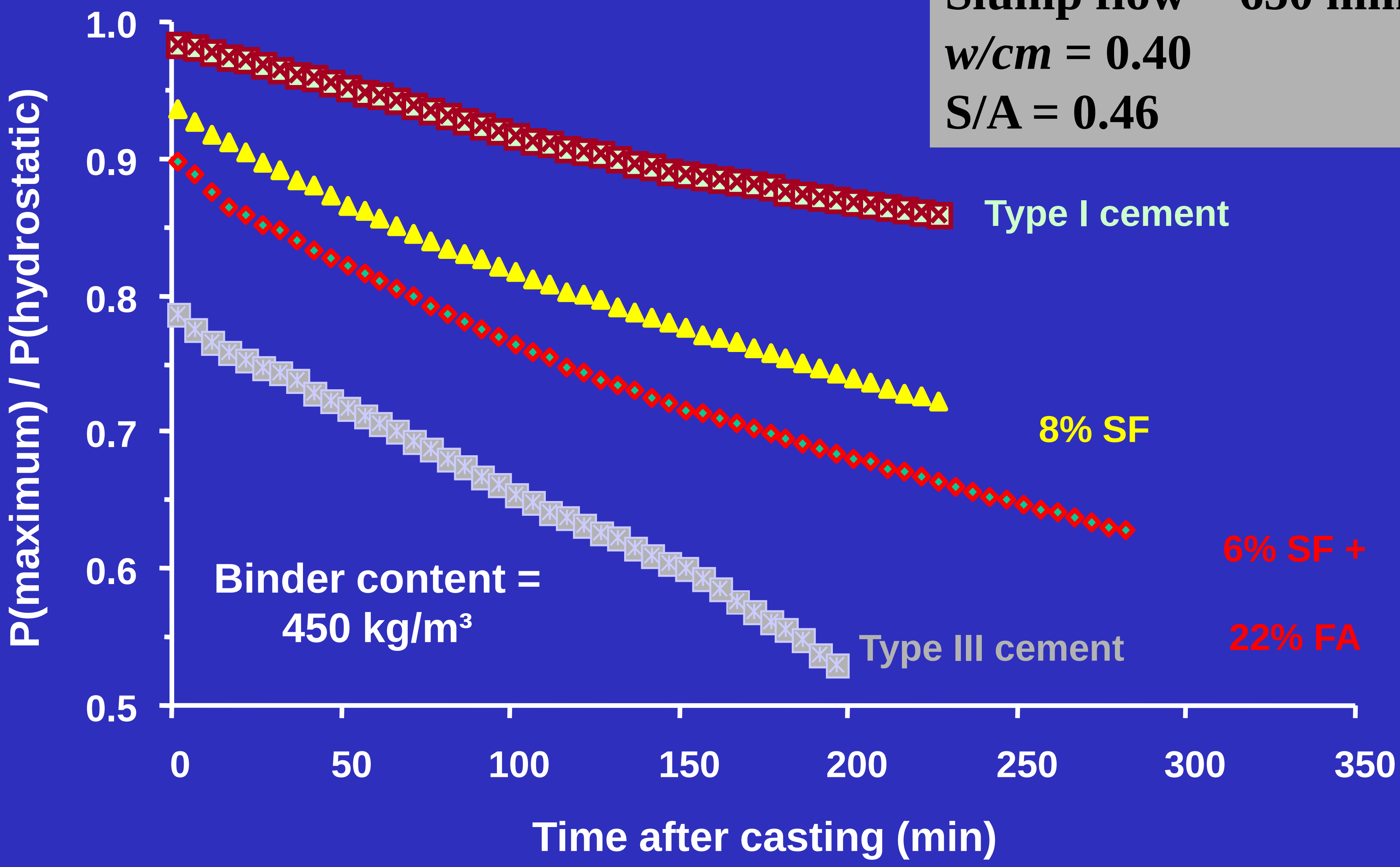
Effect of Stabilizers

Mixtures incorporating TEA exhibited the lowest initial pressure and the fastest rate of pressure drop

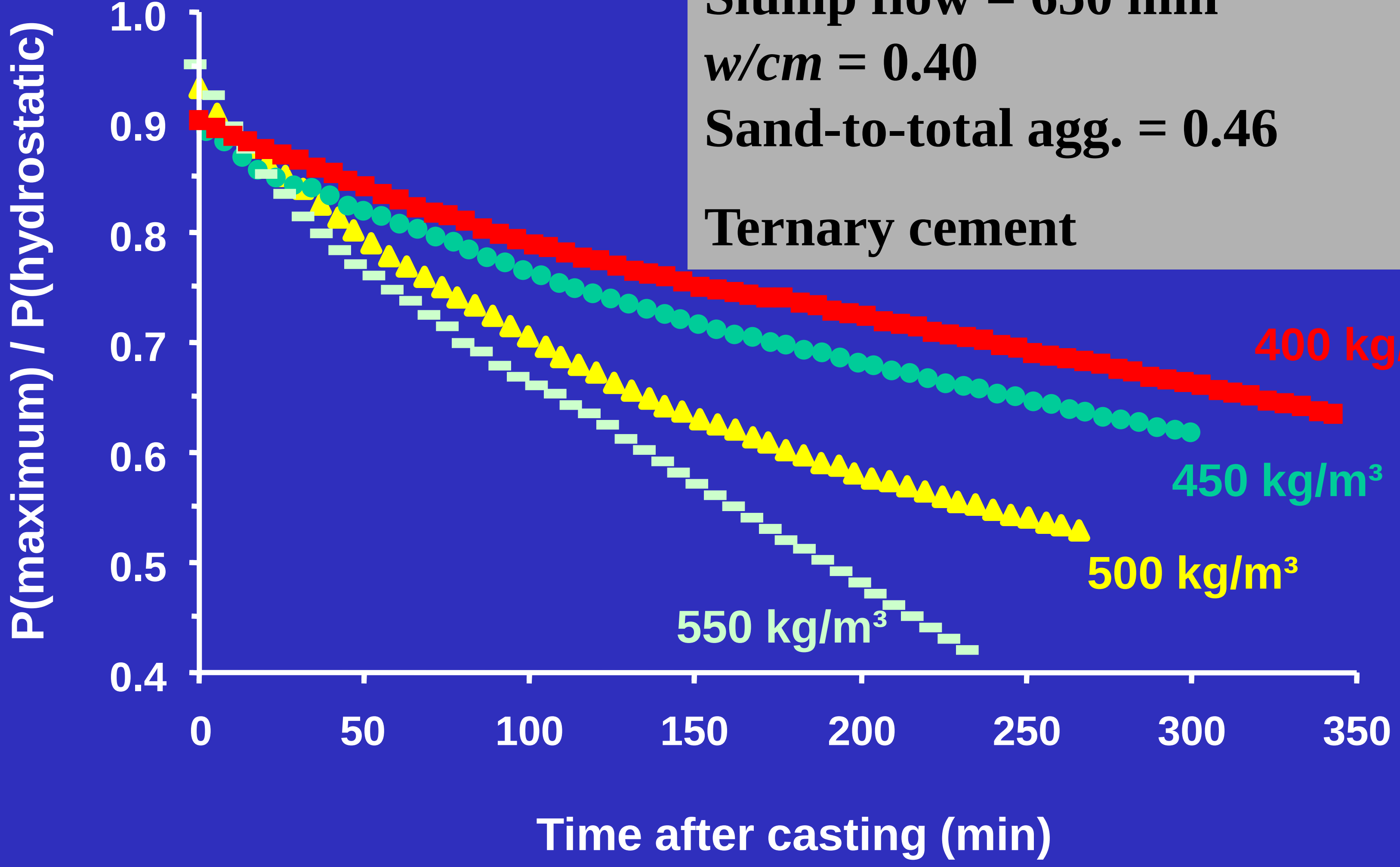
Unlike conventional VEA, increase in TEA lead to further reduction in initial pressure and increased rate of drop in pressure

Effect of Binder Type

Slump flow = 650 mm
***w/cm* = 0.40**
S/A = 0.46



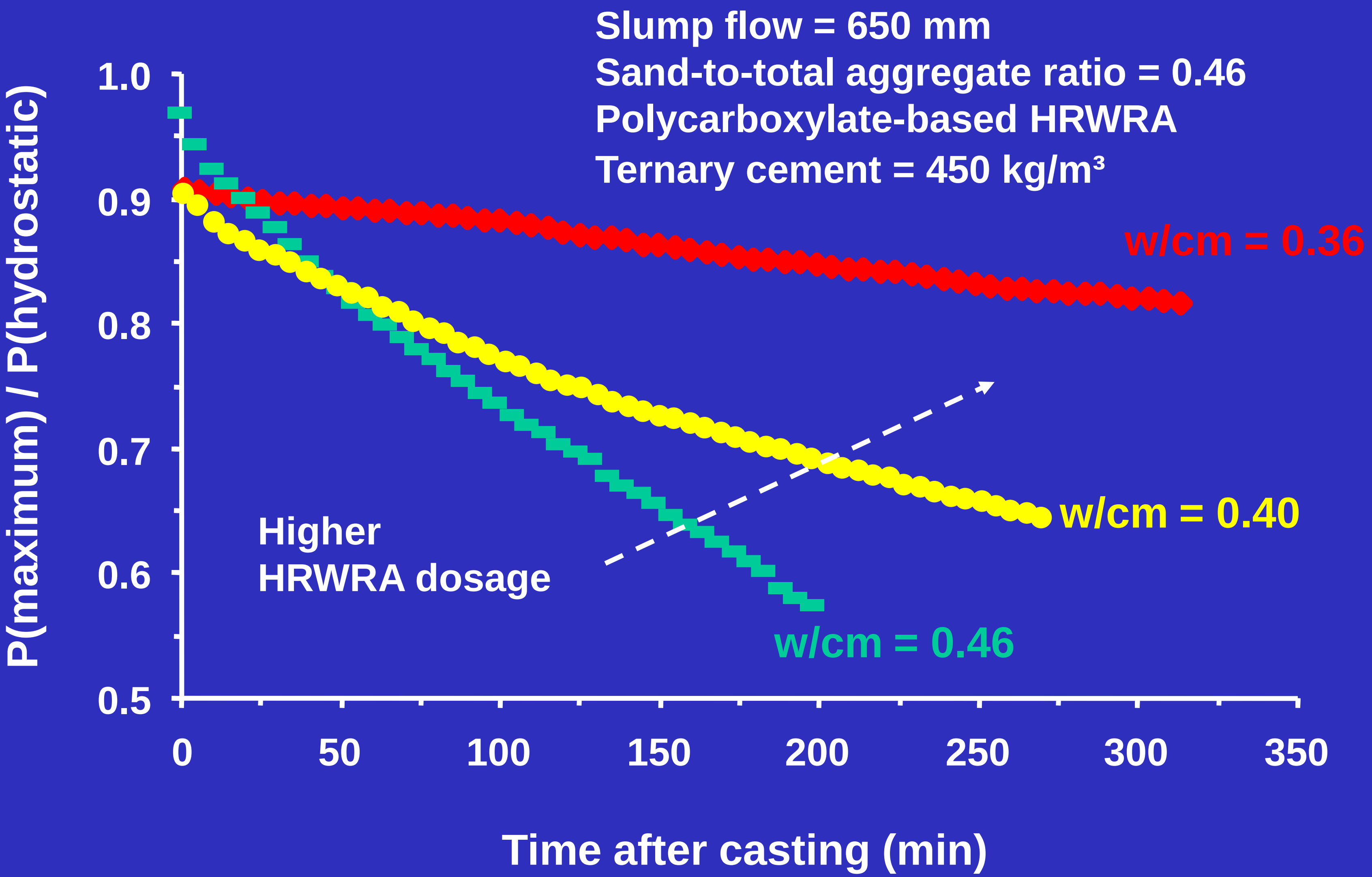
Effect of Binder Content



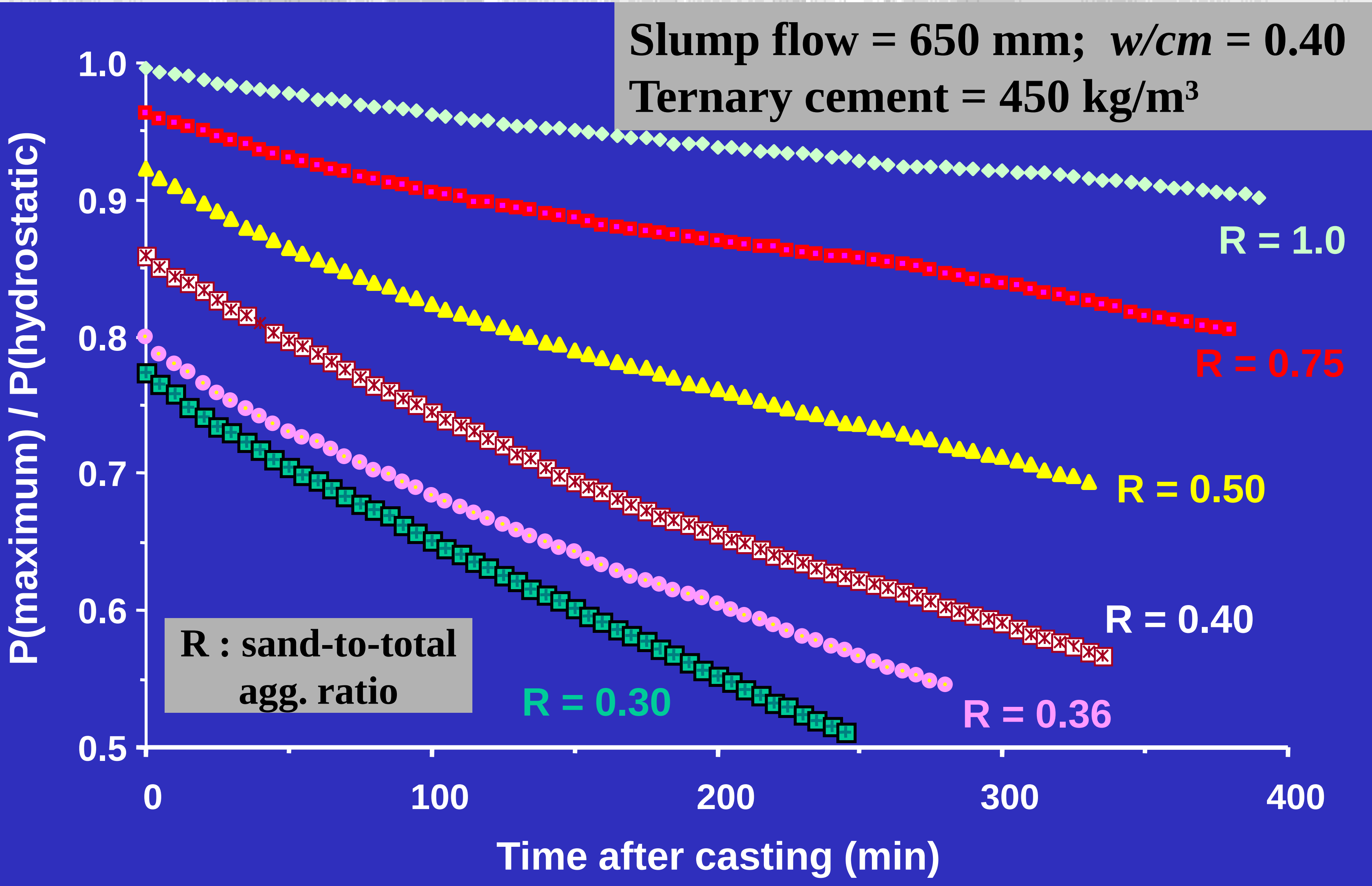
Slump flow = 650 mm
***w/cm* = 0.40**
Sand-to-total agg. = 0.46

Ternary cement

Effect of *w/cm*



Effect of S/A (Internal Friction)



Statistical models to predict: K0@Hi, ΔK(t), tc

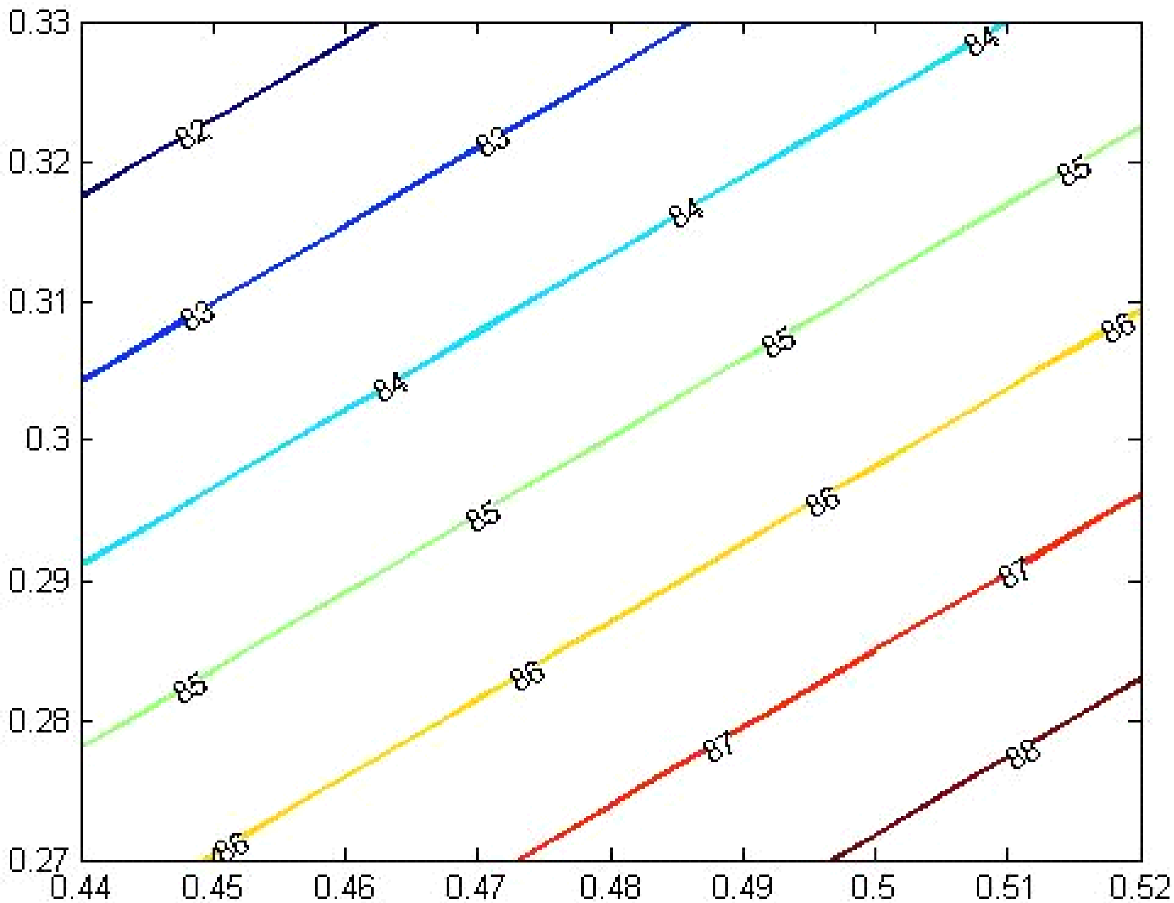
	Units	Predicting model in CODED values (ϕ, V_{ca}, S/A) = -1 to +1	R^2	Relative error 95% conf. limit (%)
K_0 at various H	%	$K_{0@H=4\ m}$ = 82 - 3.175 V_{ca} - 3.015 ϕ + 1.6875 S/A + 0.9 ϕ. V_{ca}	0.94	2.4
	%	$K_{0@H=8\ m}$ = 67.2 - 4.7275 V_{ca} + 4.0675 ϕ + 1.96 S/A + 1.1775 ϕ. V_{ca}	0.94	2.3
	%	$K_{0@H=12\ m}$ = 53.5 - 6.2775 V_{ca} + 5.1175 ϕ + 2.2325 S/A	0.91	4
ΔK(t)	%/min	ΔK(t)(0-60min) = 0.1683 + 0.0325 V_{ca} - 0.0175 S/A - 0.0075 S/A. V_{ca}	0.98	1.4
	%/min	ΔK(t)(0-t_c) = 0.16 - 0.00625 ϕ + 0.0044 S/A + 0.0006 V_{ca}	0.88	4.6
t_c	min	t_c = 587.7 - 48.56 V_{ca} + 38.06 ϕ + 24.19 S/A + 9.9375 ϕ.S/A	0.98	5.5

Contour diagrams

$K_{0@H=4m}$ (%)

ϕ = 720 mm

V_{ca}, by volume



S/A, by volume

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- Long delayed time between casting two successive SCC layers leads to reduction in interlayer bond
- Residual inter-layer bond strength is more critical in shear than in flexural or compression failure modes
- Key parameters affecting thixotropy are similar for form pressure and interlayer bonds characteristics

Conclusions 1/2

Field studies validate importance of thixotropy on form pressure characteristics

SCC of high thixotropy can exhibit:

- **lower initial lateral pressure**
- **faster drop in pressure with time**

Conclusions 2/2

Formwork pressure of SCC = f (shear strength properties)

1) Internal friction → Maximum initial pressure

(higher aggregate volume, lower binder content and w/cm, use of SCM, lower consistency level, ...)

2) Cohesion → Rate of pressure drop with time

(higher binder content, use of SCM and set-accelerator, lower HRWRA, higher temperature, lower consistency level, ...)


MTS
GB22
NAACK
TCM
PRO-CB