Field Measurements of Form Pressure Exerted by Self-Consolidating Concrete

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Dr. Khayat is active on several technical and code committees, including Chair of ACI (American Concrete Institute) 237 SCC and RILEM (International Union of Testing and Research Laboratories for Materials and Structures) Technical Committee 228 Mechanical Properties of SCC. He served as member of the Canadian Standards Association Committee A23.1/A23.2 Concrete Materials and Methods of Concrete Construction/Methods of Test for Concrete A23.1 and a number of TRB Committees.

ACI WEB SESSIONS

Test Methods to Evaluate Structural Build-up of SCC and Influence on Form Pressure

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Various Models to Evaluate Lateral Pressure

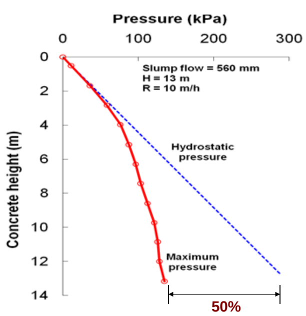
	R	T	H	Form width	Time	ρ	Thixotropy	Slump	Set time	Waiting period
1- ACI 347-04	x	x	x			x				
2- U.K. (CIRIA Report 108)	x	x	x			x				
3- Japan - Standard Specifications for Concrete Structures (2002)	x	x	x			x				
4- Sweden (Design of Vertical Concrete Formwork)	x	x							x	
5- Khayat & Assaad [2005]	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

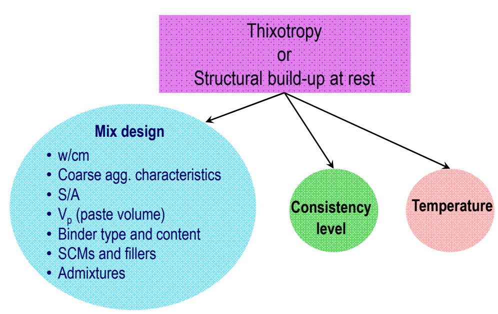
Positive Aspects of Thixotropy

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

Improved static stability



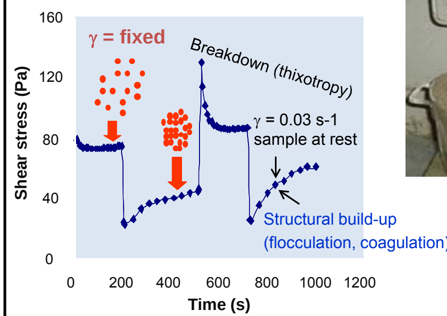
Factors Affecting Thixotropy of Concrete



Outline

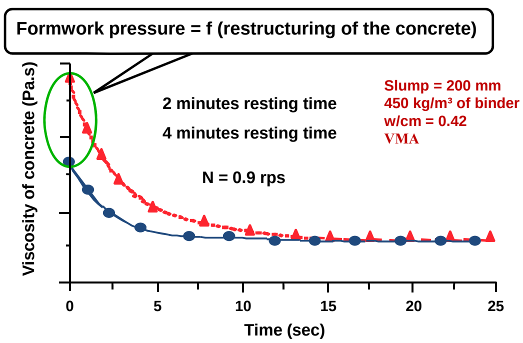
- Thixotropy determination:
  - structural breakdown
  - structural build-up at rest
- Thixotropy vs. form pressure exerted by SCC

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

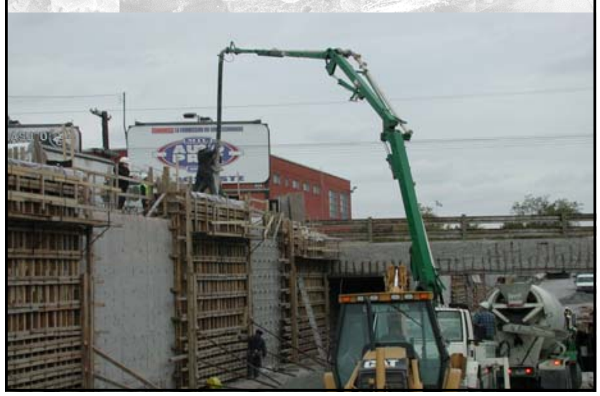


Modified MK-III rheometer

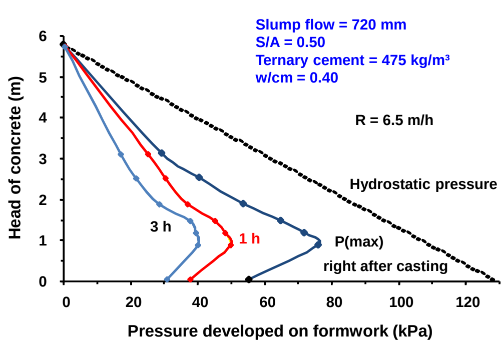
Importance of Restructuring !



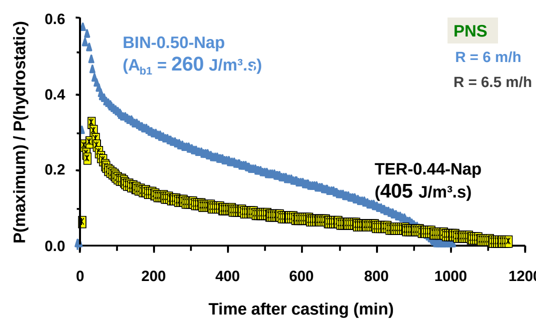
R ~ 6-10 m/hr



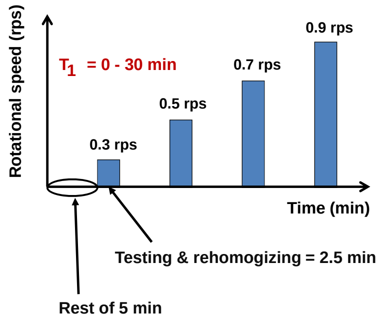
Typical Formwork Pressure Envelops



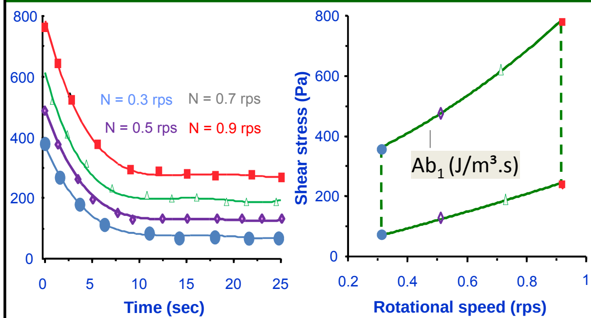
Pressure Variations with Thixotropy



Time Intervals for Assessing Thixotropy



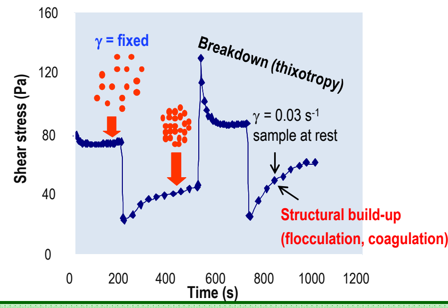
1. Structural breakdown: structural breakdown area (Ab_1)



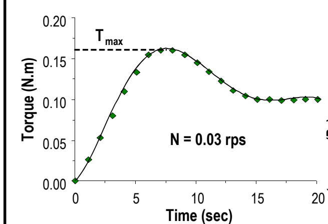
Lapasin et al. [1983] $Ab_1 = \int_{0.3}^{0.9} (\tau_i(N) - \tau_e(N))\,dN$ $J/m^3.s$

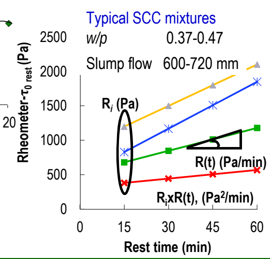
Structural build-up at rest: Re-structuring

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



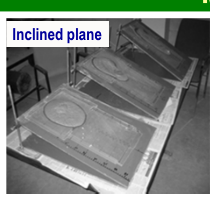
Static Shear Stress at Rest (τ_{0rest})





Field-Oriented Tests to Evaluate Thixotropy of Flowable Mortar and SCC

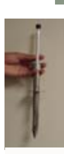
Inclined plane



Portable vane

Cone penetration

Falling ball

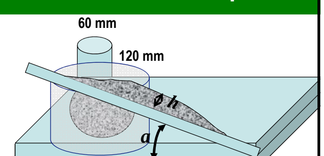


K-Slump

Undisturbed slump spread

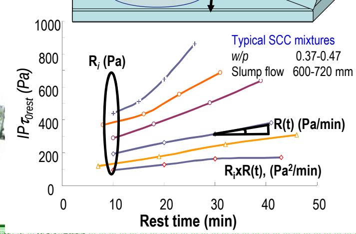
Inclined Plane (IP) Test Free Surface Flow of Thixotropic Fluid

Mortar

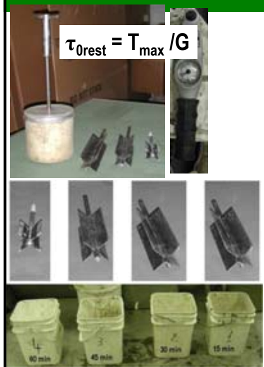


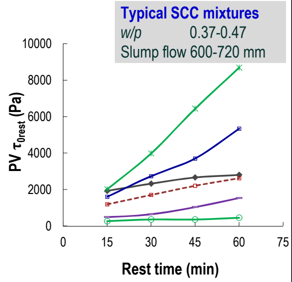
$$IP\tau_{0rest} = \rho g h \sin\alpha$$

Concrete



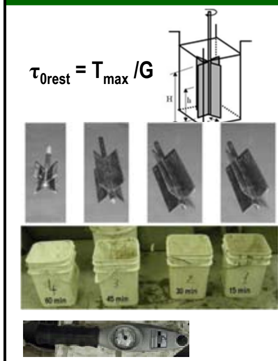
Portable Vane (PV) Test

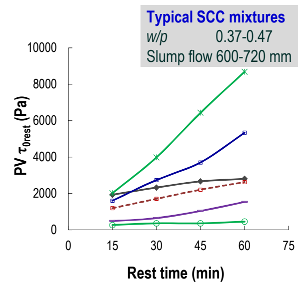




R_i (Pa) R(t), (Pa/min) R_ixR(t), (Pa^2/min)

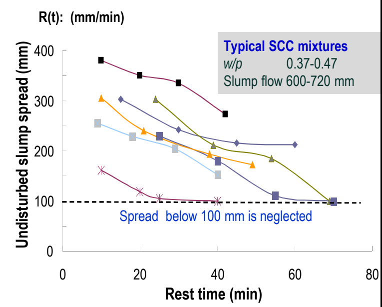
Portable Vane (PV) Test





Portable Vane (PV) Test

Undisturbed Slump Spread (USS) Test



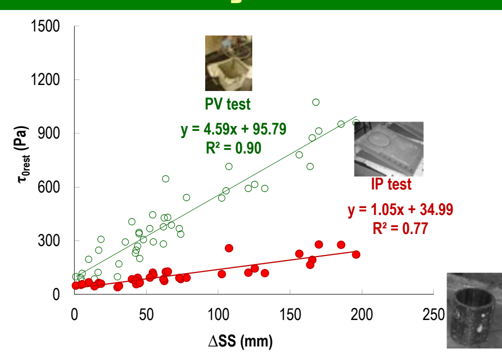
USS = $(D_1+D_2)/2$

Relative Errors (%) of Tests using SCC Mixtures

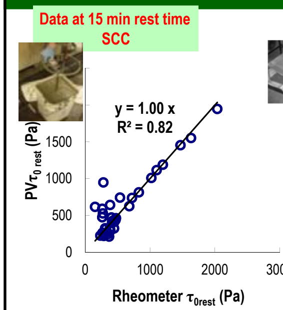
	Rest time (min)	PV test
Thixotropic SCC	15	19
	30	12
	45	9

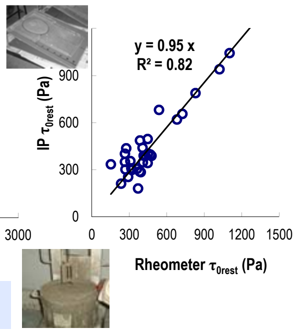
Rest time (min)	IP test
15	8
20	8
25	8
30	5

Correlations using CEM Mixtures



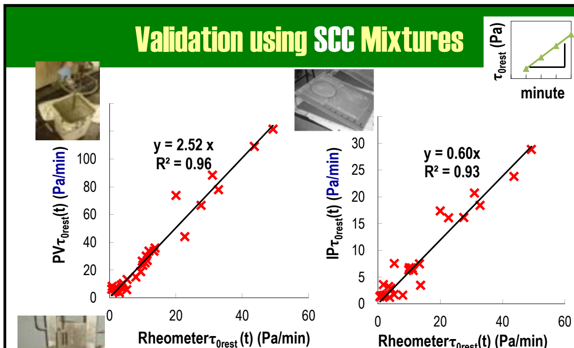
Yield Stress at Rest: PV and IP Tests vs. Rheometer





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

Validation using SCC Mixtures



Good relationship between evolution of PV and IP static yield stress with time and the evolution of static yield stress from concrete rheometer

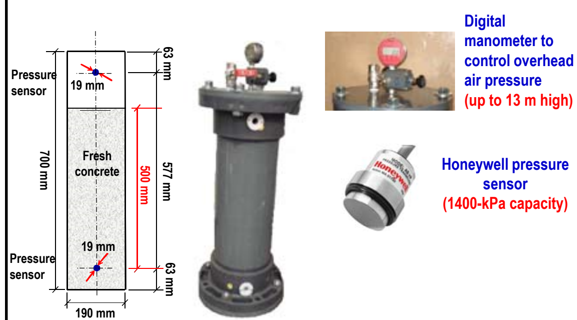
Thixotropy as Input to Evaluate Formwork Pressure

$$P_{max} = \rho g H\,[a_1 H + a_2 R + a_3 T + a_4 D_{min} + a_5 TI_{@fixed\ Temp.}]$$

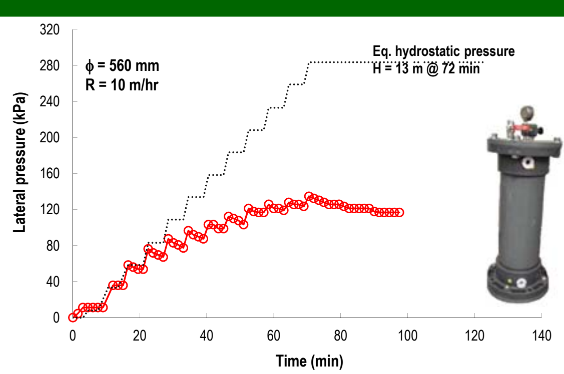
$$P_{max} = \rho g H\,[a_1 H + a_2 R + \cancel{a_3 T} + a_4 D_{min} + a_5 TI_{@various\ Temp.}]$$

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

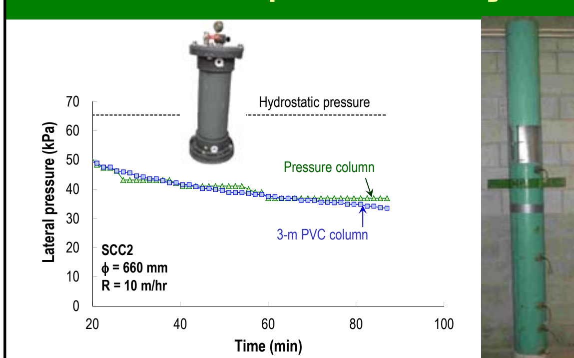
Pressure Device to Determine Lateral Pressure



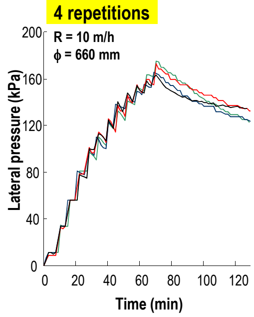
Pressure Variations

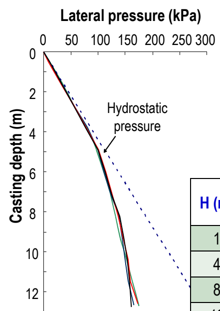


Validation: Pressure Response vs. 3-m Standing Column



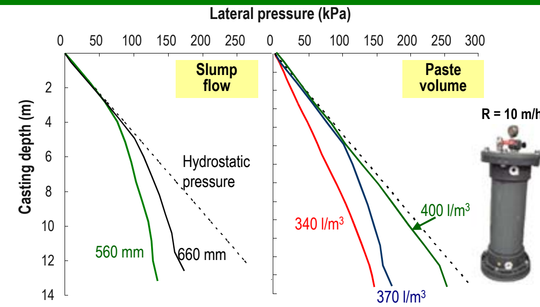
Repeatability of Pressure Responses





H (m)	RE (%)
1	± 0.7
4	± 2.4
8	± 2.3
12	± 4.0

Validation: Effect of Slump Flow & Paste Volume



Effect of different slump flow values and paste volumes on lateral pressure envelopes

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

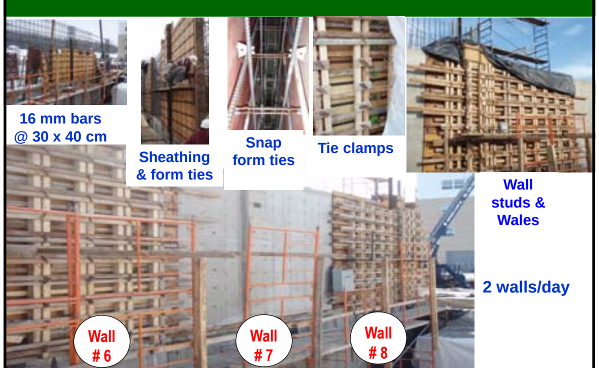
$PV\tau_{0rest@15min}$ = 1200 Pa

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



Investigated Parameters

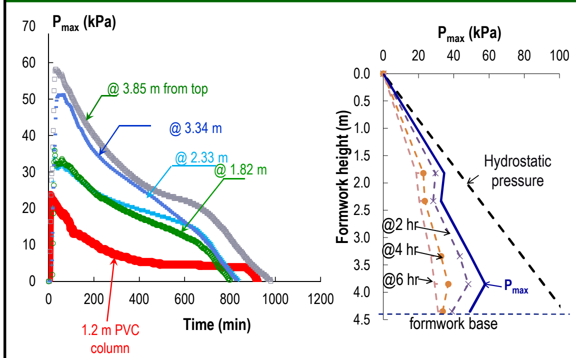
	Level 1000, H = 3.7 m (effect of casting rate)				Level 2000, H = 4.4 m (effect of thixo.)			
	Wall #1 VCC	Wall #2 SCC1	Wall #3 SCC1	Wall #4 SCC1	Wall #5 VCC	Wall #6 SCC1	Wall #7 SCC2	Wall #8 SCC3
Slump/ slump flow (mm)	120 ± 30	650 ± 25			120 ± 30	650 ± 25		
HRWRA type	---	PCP			---	PCP		PNS
Vp (L/m³)	---	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 Material Characterization

10 persons to carry out > 17 tests

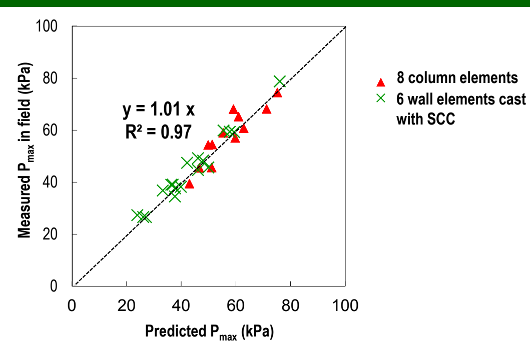
Lateral pressure [wall # 6, SCC1, R = 10 m/h]



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	--

Predicted vs. Field Measurements



Conclusions

- Thixotropy can be assessed by structural breakdown and structural build-up at rest
- Structural breakdown area is determined using rheometer
- Structural build-up at rest can be determined using the structural growth approach - variations of static yield stress at rest - using:
  - rheometer
  - empirical tests: inclined plane / portable vane test methods

➢ Static yield stress of inclined plane / portable vane tests correlate well to that of concrete rheometer

➢ Increase of thixotropy leads to reduction in lateral formwork pressure exerted by SCC

➢ Field validation results are encouraging

Test Methods to Evaluate Thixotropy

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2. Omran AF, Khayat KH (2011) Choice of Thixotropic Index to Evaluate Formwork Pressure Characteristics of Self-Consolidating Concrete. *Submitted to J. of Cem. and Con. Res.*: 34.
3. Omran AF, Naji S, Khayat KH (2011) Portable Vane Test to Assess Structural Build-Up at Rest of Self-Consolidating Concrete. *ACI Mat. J.*, 108(6):628-637.
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5. Khayat KH, Omran AF (June 2011) Field Validation of SCC Formwork Pressure Prediction Models. *J. of Con. Inter.*, 33(Issue 6):33-39.
6. Khayat KH, Omran AF, D'Ambrosia M (Sept. 2010) Prediction of SCC Formwork Pressure in Full-Scale Elements. *Proceedings of 6th International RILEM Symposium on SCC, and 4th North American Conference on Design and Use of SCC (SCC2010), Montreal, Canada, RILEM State of the Art Reports*, Vol.1(Part 6):231-242.
7. Khayat KH, Omran AF (July/August, 2009) Evaluation of SCC formwork pressure. *Concrete Infocus Magazine, a Publication of the National Ready Mixed Concrete Association – SCC: Developing Guidelines to Lower Lateral Pressure*:16-19.
8. Khayat KH, Omran AF (June 2009) Evaluation of SCC Formwork Pressure. *Proceedings of 2nd Inter. Sym. on Design, Performance and Use of SCC (SCC2009), Eds. C Shi, Z Yu, KH Khayat, P Yan, RILEM Publications sarl, Beijing, China*:43-55.
9. Khayat KH, Omran AF, Naji S, Billberg P, Yahia A (Nov. 2008) Test Methods to Evaluate Form Pressure of SCC. *Proceedings of 3rd North American Conference on Design and Use of SCC (SCC 2008), Eds. Shah SP, Chicago*:308-314.