Optimization of steam-curing regime for high-strength, self-consolidating concrete for precast, prestressed concrete applications

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- This study examined the effects of various steam-curing parameters on the early-age compressive strength and modulus of elasticity of self-consolidating concrete (SCC).
- For the 80 MPa (11,600 psi) SCC, the maximum chamber temperature had the most significant effect on both strength and modulus of elasticity, followed by the rate of heating and the length of the preset period.
- For the 60 MPa (8700 psi) SCC and high-performance concrete, steam curing appeared to provide little additional benefit in terms of early-age strength.

Self-consolidating concrete (SCC) can flow through densely reinforced or geometrically complex structural elements under its own weight and adequately fill the formwork with minimum segregation.[1] Because of its high workability and high early strength, SCC is widely used in the fabrication of precast concrete elements with complex geometry. Such concrete can provide good surface finish and enhance productivity. The use of SCC opens the way for automation of concrete construction and concrete product in manufacturing processes. SCC permits the production of virtually any cross section. Sections with dense reinforcement and bottlenecks at built-in fittings can be properly cast using SCC. Fewer and smaller air bubbles form on the underside of horizontal formwork. The surface can be smoother and more uniformly colored than those with conventional vibrated concrete of normal consistency.

The gain of early-age compressive strength in steam-cured concrete is affected by mixture composition and curing parameters. The curing temperature is held constant once it attains the maximum chamber temperature. Following the maximum chamber temperature period, the temperature cools to ambient temperature. **Table 1** summarizes recommendations and regulations regarding steam curing as given by the Canadian Standards Association (CSA),[2]

Table 1. Comparison of code requirements for steam curing

Code	Preset period	Maximum rate of heating, °C/hr	Maximum temperature, °C	Maximum rate of cooling, °C/hr
CSA A23.4	After initial set, at least 3 hours after final placement	20	70 for dry conditions 60 for damp conditions	15
Korea Concrete Institute	2 to 3 hours	20	65	Not specified
***PCI Bridge Design Manual*, MNL-133-97**	3 to 5 hours after initial set	11 to 44	77 65 to prevent DEF *PCI Manual for Quality Control for Plants and Production of Structural Precast Concrete Products* (MNL-116-99)	Not specified
Portland Cement Association 2006	3 to 5 hours after initial set, at least 3 hours after final placement	11 to 22	71 60 is recommended	22
ACI 517.2R-87 (1992)	Close to initial set	11 to 44	82	6
***AASHTO LRFD Bridge Design Specifications*, 2004**	After initial set	22	71	22
Texas DOT 2004	After initial set, at least 3 hours after final placement	20	Do not exceed 77 Do not exceed 71°C for more than 1 cumulative hour during curing period	Not specified
Florida DOT 2004	After initial set, apply heat (5.5°C/hr) during preset period when ambient temperature is below 10°C	20	71 with variation of no more than 10 from maximum temperature	28 until concrete temperature reaches 22°C
New York State DOT 2002	After initial set	20	Maintain temperature between 40 and 85 for a period of not less than 12 hours	20
Washington DOT 2002	After initial set, heat concrete to no more than 38°C during first 2 hours after placement	14	80	14 until concrete temperature reaches 38°C

Note: DOT = department of transportation. °C = (°F – 32)/1.8.

PCI,[3] the Portland Cement Association (PCA),[4] the American Concrete Institute (ACI),[5] the American Association of State Highway and Transportation Officials (AASHTO),[6] four state departments of transportation (DOTs) in the United States,[7–10] and the Korea Concrete Institute.[11] Requirements for maximum chamber temperature, preset period, rate of heating, and rate of cooling are set to secure favorable mechanical properties and durability and to minimize surface defects and cracking.

In general, increases in maximum chamber temperature can lead to improvements in early-age mechanical properties. The maximum curing temperature as found in various codes ranges from 40°C to 85°C (104°F to 185°F). Such a wide range may be related to the difference in the targeted 18-hour compressive strength and the diversity of chemical and physical characteristics of the cement and supplementary cementitious materials in use. The limit on maximum temperature is set to mitigate any adverse effects of high curing temperatures on the long-term development of strength and durability.

Heat treatment affects microstructure development and properties of the hardened cement paste.[4,12–14] The morphology and length of ettringite crystals seem to be strongly dependent on curing temperature and can lead to expansion and cracking.[15] Steam curing also affects the pore structure of the hydrated cement paste by increas-

ing the proportion of large pores. As a result, the ultimate strength of steam-cured concrete could be lower than that of standard-cured concrete. To minimize the reduction in ultimate strength and the potential for delayed ettringite formation, the concrete temperature should not exceed 70°C (158°F).[4,12–14] The Canadian and German standards[2,16,17] limit the maximum concrete curing temperature to 60°C (140°F) for concrete exposed to damp conditions in service. CSA says that damp conditions apply to concrete elements exposed to a moist environment during service or non-air-entrained concrete exposed to a moist environment for more than 3 months prior to service.[2]

For precast concrete products, PCI[18] proposes a maximum allowable concrete curing temperature of 65°C (149°F). For minimum risk, it is recommended that the concrete not be cured above 60°C (140°F) for applications regularly exposed to significant moisture, unless the cement is proved to be safe when cured at higher temperature.[19] This is consistent with guidelines provided in the German standards and CSA.

As in the case of maximum temperature, early-age mechanical properties can improve with the length of the preset period. For example, early-age strength increases consistently with increasing preset period from 3 to 5 hours, depending on the maximum curing temperature and binder type.[4,20] Beyond the maximum limit, however, the early-age strength decreases with increases in the preset period.[4,20] Most of the code regulations recommended that steam curing be applied after the initial set or at least 3 hours after concrete placement. Given the relatively low water–cementitious material ratio (*w/cm*) of concrete in precast, prestressed concrete applications, 3 to 5 hours is the normal preset period to obtain adequate early-age strength development.

The rate of heating during steam curing should be adjusted to ensure proper performance. As in the case of the maximum curing temperature and preset period, an increase in the rate of heating up to a certain limit can increase the 18-hour early-age compressive strength. Codes recommend a rate of heating that varies from 11°C/hr to 44°C/hr (20°F/hr to 79°F/hr). As indicated in Table 1, many standards limit the maximum rate of heating to 20°C/hr to 22°C/hr (36°F/hr to 40°F/hr) to avoid detrimental cracking due to large temperature gradients during heating.

Limited work has been done to investigate the effect of steam-curing parameters on strength development of high-strength SCC. This paper reports the results of work undertaken to evaluate the effect of the steam-curing regime on mechanical properties for SCC with design compressive strengths of 60 and 80 MPa (8700 and 11,600 psi). The factorial design approach was used in this investigation as a statistical tool to quantify the effect of steam-curing parameters on the early mechanical properties of SCC in precast, prestressed concrete applications.

Experimental program

Materials

CSA Type GU (general use) cement, similar to ASTM C150 Type I cement, Class F fly ash (FA), and silica fume (SF) were used. The specific gravities of the cement, fly ash, and silica fume are 3.14, 2.53, and 2.22, respectively. Continuously graded crushed limestone aggregate with a maximum size of aggregate (MSA) of 19 mm (0.75 in.) and well-graded siliceous sand were employed. The coarse aggregate and sand have fineness moduli of 6.4 and 2.5, bulk specific gravities of 2.72 and 2.64, and absorption values of 0.28% and 1.39%, respectively. The mixtures were proportioned with two types of polycarboxylate-based high-range water-reducing admixtures (HRWRAs) complying with ASTM C494 Type F. Such admixtures are widely used in the precast concrete industry in North America. The first type is designed for high-early-strength development, and the second for normal strength development. Specific gravity and solid contents of the former are 1.07 and 32%, respectively, and for the latter 1.05 and 27%, respectively.

Scope of work

The investigation is divided into two phases. Phase 1 was undertaken to evaluate the effect of key mixture parameters on workability, compressive-strength development, and modulus of elasticity of high-strength SCC. **Table 2** presents the experimental program of phase 1. Two optimized SCC mixtures with 56-day design compressive strengths of 60 and 80 MPa (8700 and 11,600 psi) were developed and used in the second phase to evaluate the effect of steam-curing parameters on early-strength development. A two^{1-4} fractional factorial design with four main factors, each at two levels, was used as follows:

- binder content: 450 and 550 kg/m^3 (761 and 930 lb/yd^3)
- *w/cm*: 0.28 and 0.38
- HRWRA type: high-early-strength and normalstrength polycarboxylate-based HRWRA
- binder type: Type GU cement with 20% Class F fly ash or 7% silica fume replacement

The targeted release compressive strength for the SCC is 30 MPa (4350 psi) after 18 hours of steam curing and 70 and 90 MPa (10,150 and 13,050 psi) after 56 days of moist curing. The factorial design in Table 2 also includes three mixtures corresponding to the central point. The HRWRA dosage was adjusted to achieve a constant slump flow of 680 ± 20 mm (27 ± 0.8 in.) at 10 minutes following cement-to-water contact. The SCC mixtures were not air

Table 2. Experimental program to investigate influence of key mixture parameters on properties of SCC, phase 1

Type	Mixture number	Coded values				Absolute values			
		w/cm	Binder content	HRWRA type	Binder type	*w/cm*	Binder content	HRWRA type	Binder type
SCC: 660 to 700 mm slump flow at 10 minutes	1	-1	-1	-1	-1	0.28	450	NS	GU + 20% FA
	2	-1	-1	1	1	0.28	450	HES	GU + 7% SF
	3	-1	1	-1	1	0.28	550	NS	GU + 7% SF
	4	-1	1	1	-1	0.28	550	HES	GU + 20% FA
	5	1	-1	-1	1	0.38	450	NS	GU + 7% SF
	6	1	-1	1	-1	0.38	450	HES	GU + 20% FA
	7	1	1	-1	-1	0.38	550	NS	GU + 20% FA
	8	1	1	1	1	0.38	550	HES	GU + 7% SF
Central point	9–11*	(three replicate mixtures)							
HPC	12–13	Normal consistency mixtures with 180 mm slump							
		w/cm of 0.28 with type GU + 7% SF (HPC mixture design)							
		w/cm of 0.38 with type GU + 20% FA (HPC mixture design)							

*Mixtures 9 through 11 were made with *w/cm* of 0.33, binder content of 500 kg/m^3, HES or NS HRWRA, Type GU + 20% FA or 7% SF
Note: FA = Class F fly ash; GU = general use; HES = high-early-strength; HPC = high-performance concrete; HRWRA = high-range water-reducing admixture; NS = normalstrength; SCC = self-consolidating concrete; SF = silica fume; *w/cm* = water–cementitious material ratio, by mass.
1 mm = 0.0394 in.; 1 kg/m^3 = 1.685 lb/yd^3.

entrained and were proportioned with a fixed sand–to–total aggregate volume ratio of 0.50. In addition to the SCC mixtures, two normal-consistency high-performance concrete (HPC) mixtures that are representative of mixtures employed for precast concrete structural elements were included in the test program in phase 1.

The SCC and HPC mixtures in phase 1 were subjected to a fixed steam-curing regime. The regime involves a preset period of 2 hours, a rate of heating of 20°C/hr (36°F/hr), a maximum chamber temperature of 60°C (140°F), and a cooling rate of 15°C/hr (27°F/hr).

Based on the properties of the mixtures investigated in phase 1, two SCCs with 56-day design compressive strengths of 80 MPa (11,600 psi) (SCC1) and 60 MPa (8700 psi) (SCC2) were selected. The SCC mixtures were subjected to various steam-curing regimes to evaluate the effect of steam curing on compressive strength and elastic modulus. Steam-curing parameters included the preset period, maximum chamber temperature, and rate of heating. Each modeled parameter was considered at two levels. Eight and four different curing regimes were applied to SCC1 and SCC2, respectively (**Table 3**). The optimum steam-curing regime was applied to the HPC1 and HPC2 mixtures.

Each concrete was tested for compressive strength and modulus of elasticity using standard cylinders (100 × 200 mm [4 × 8 in.]). Modulus of elasticity was determined at 18 hours on steam-cured cylinders. Compressive strength was determined on samples subjected to both air and steam curing. Additional cylinders were moist cured and tested for compressive strength at 7, 28, and 56 days as well as for elastic modulus at 56 days.

Mixing and sampling

The SCC mixtures were prepared in 100 L (3.53 ft^3) batches using a drum mixer. The mixing sequence consisted of wetting the sand and coarse aggregate with half of the mixing water, followed by a binder addition. Once the aggregate particles were coated with a layer of cement paste, the remaining water and HRWRA were introduced over 30 seconds, and the concrete was mixed for 2.5 minutes. The concrete remained at rest in the mixer for 3 minutes for fluidity adjustment (680 ± 20 mm [27 ± 0.8 in.]). This enabled large entrapped air bubbles to rise to the surface. The concrete was remixed for 2 minutes and then tested for workability characteristics. The concrete was agitated at 6 rpm between the ages of 10 minutes and 40 minutes. After the evaluation of properties at 40 minutes, several cylinders were sampled. The specimens were cast in one lift without any mechanical consolidation. Some of the sam-

Table 3. Experimental program to evaluate the effect of steam-curing parameters on mechanical properties of SCC, phase 2

Type	Batch number	Coded value			Absolute value		
		Maximum chamber temperature, °C	Rate of heating, °C/hr	Preset period, hours	Maximum chamber temperature, °C	Rate of heating, °C/hr	Preset period, hours
SCC1, eight curing regimes	1	-1	-1	-1	50	12	2
	2	-1	-1	1	50	12	5
	3	-1	1	-1	50	22	2
	4	-1	1	1	50	22	5
	5	1	-1	-1	60	12	2
	6	1	-1	1	60	12	5
	7	1	1	-1	60	22	2
	8	1	1	1	60	22	5
Central points SCC1, 80 MPa SCC	9	0	0	0	55	17	3.5
	10	0	0	0	55	17	3.5
	11	0	0	0	55	17	3.5
SCC2, four curing regimes, 60 MPa SCC	12	-1	-1	1	50	12	5
	13	-1	1	-1	50	22	2
	14	1	-1	-1	60	12	2
	15	1	1	1	60	22	5
HPC1	16*	1	1	1	60	22	5
HPC2	17†	1	1	1	60	22	5

* Mixture 16 was made with *w/cm* of 0.28 with Type GU + 7% SF (HPC mixture design).
† Mixture 17 was made with *w/cm* of 0.38 with Type GU + 20% FA (HPC mixture design).
Note: FA = Class F fly ash; GU = general use; HPC = high-performance concrete; SCC = self-consolidating concrete; SF = silica fume; *w/cm* = water–cementitious material ratio, by mass. 1 mm = 0.0394 in.; 1 MPa = 0.145 ksi; 1 GPa = 145 ksi; 1 kg/m^3 = 1.685 lb/yd^3; °C = (°F – 32)/1.8.

ples were covered and stored at 23°C ± 2°C (73°F ± 4°F) for air curing at a relative humidity of 50% ± 5%, while others were steam cured, as indicated earlier.

Workability test methods

Workability of SCC was evaluated using the slump flow (ASTM C1611), L-box, J-ring (ASTM C 621), and surface settlement tests. Rheological properties (yield stress and plastic viscosity) of the concrete were determined using a modified two-point concrete rheometer. In addition to the J-ring test, the L-box test was used to evaluate the passing ability. The blocking ratio (h_2/h_1) is calculated where h_1 and h_2 correspond to the heights of the SCC remaining in the vertical section and at the leading edge of the apparatus, respectively. The static stability of SCC after casting until the time of hardening was assessed using the surface settlement test.[21]

Test results

Effect of key mixture parameters on properties of SCC

In total, 13 concrete mixtures were designed with various mixture parameters to model the properties of the fresh and hardened SCC. **Table 4** presents the proportioning of these concrete mixtures. **Table 5** gives the yield stress, plastic viscosity, and mechanical properties. These results are employed to derive statistical models for each of the investigated properties. The statistical models are used to quantify and rank the affecting mixture parameters on the properties of SCC.

Table 6 presents the derived statistical models for the properties of the fresh concrete expressed in terms of coded values. The correlation coefficient R^2 values of the derived models ranged from 0.92 to 0.99. A negative estimate signifies that an increase in the modeled param-

Table 4. Mixture proportioning of SCC and HPC mixtures in phase 1

w/cm binder content-HRWRA type-(SF or FA)		SCC1 28-450-NS-FA	SCC2 28-450-HES-SF	SCC3 28-550-NS-SF	SCC4 28-550-HES-FA	SCC5 38-450-NS-SF	SCC6 38-450-HES-FA	SCC7 38-550-NS-FA	SCC8 38-550-HES-SF	SCC9 33-500-NS-SF	SCC10 33-500-NS-SF	SCC11 33-500-NS-SF	HPC1	HPC2
w/cm		0.28	0.28	0.28	0.28	0.38	0.38	0.38	0.38	0.33	0.33	0.33	0.28	0.38
Type GU cement, kg/m³		360	419	512	440	419	360	440	512	465	465	465	437	376
Silica fume, kg/m³		0	312	39	0	32	0	0	39	35	35	35	33	0
Class F fly ash, kg/m³		90	0	0	110	0	90	110	0	0	0	0	0	94
Total binder, kg/m³		450	450	550	550	450	450	550	550	500	500	500	470	470
Sand, kg/m³		931	938	850	853	872	876	782	786	865	865	865	738	686
Coarse aggregate, kg/m³		962	964	875	878	898	902	805	809	891	891	891	1140	1059
Sand–to–total aggregate ratio by volume		0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.4
HRWRA, L/m³	HES	0	16.5	0	8.0	0	1.90	0	2.87	0	0	0	0.5	1.4
	NS	10.0	0	9.0	0	4.0	0	2.17	0	6.55	6.6	7.5	0	0

Note: FA = fly ash; GU = general use; HES = high-early-strength; HPC = high-performance concrete; HRWRA = high-range water-reducing admixture; NS = normalstrength; SCC = self-consolidating concrete; SF = silica fume; *w/cm* = water–cementitious material ratio, by mass. 1 mm = 0.0394 in.; 1 MPa = 0.145 ksi; 1 GPa = 145 ksi; 1 kg/m³ = 1.685 lb/yd³; L/m³ = 7.475 × 10^{-3} gal./ft³; °C = (°F – 32)/1.8.

eter can lead to a reduction in the measured response. For example, in the case of the T-50 model, an increase in *w/cm* can decrease the T-50 time. The *w/cm* had the most significant effect on workability, followed by the binder content. The type of binder exhibited considerable effect on HRWRA demand and low to moderate effect on the other investigated properties. Mixtures made with Type GU and 20% Class F fly ash had lower HRWRA demand than those prepared with 7% silica fume replacement.

The type of HRWRA had a significant effect on passing ability. Based on the derived models in Table 6, SCC made with a high-early-strength (HES) type of HRWRA can exhibit a higher passing ability (higher J-ring flow) and a lower spread between slump flow and J-ring flow values than a similar SCC prepared with normalstrength (NS)-type HRWRA.

Table 7 presents the derived statistical models for compressive strength and modulus of elasticity. As expected, the *w/cm* had the most significant effect on mechanical properties, except for the 18-hour air-cured compressive strength. The binder type also showed considerable influence on mechanical properties. SCC made with 7% silica fume replacement developed a higher compressive strength at 18 hours, 28 days, and 56 days and a higher elastic modulus at 18 hours compared with those prepared with 20% Class F fly ash replacement. As presented in Table 7, the binder content exhibited low or moderate influence on mechanical properties. On the other hand, the type of HRWRA had considerable effect on the 18-hour air-cured compressive strength. As expected, SCC mixtures prepared with HES-type HRWRA can develop a higher 18-hour air-cured compressive strength than those with NS-type HRWRA. The influence of the HRWRA type on the 18-hour steam-cured strength was shown to vary with *w/cm* in use.

Selection of optimized mixtures

Based on the statistical models derived from the factorial design, **Table 8** summarizes mixture proportions for SCC with 56-day design compressive strengths of 60 and 80 MPa (8700 and 11,600 psi). SCC made with 0.38 *w/cm* exhibited superior passing ability and filling capacity compared with SCC prepared with 0.28 *w/cm*. On the other hand, the latter developed greater compressive strength and elastic modulus.

As presented in Table 8, mixtures made with Type GU cement and 7% silica fume replacement developed a higher compressive strength and elastic modulus compared with

Table 5. Properties of SCC and HPC mixtures investigated in phase 1

w/cm binder content-HRWRA type-(SF or FA)	SCC1 28-450-NS-FA	SCC2 28-450-HES-SF	SCC3 28-550-NS-SF	SCC4 28-550-HES-FA	SCC5 38-450-NS-SF	SCC6 38-450-HES-FA	SCC7 38-550-NS-FA	SCC8 38-550-HES-SF	SCC9 33-500-NS-SF	SCC10 33-500-NS-SF	SCC11 33-500-NS-SF	HPC1	HPC2
Slump flow (T-50) at 10 minutes, mm (sec)	670 (35.4)	665 (41.0)	670 (16.5)	690 (8.8)	690 (3.11)	670 (2.02)	670 (0.67)	660 (0.80)	670 (2.82)	670 (3.72)	670 (3.77)	190*	190*
Slump flow (T-50) at 40 minutes, mm (sec)	670 (32.2)	680 (39.2)	660 (22.5)	700 (8.5)	690 (2.26)	690 (1.47)	640 (0.54)	700 (0.93)	630 (6.35)	610 (6.7)	620 (7.02)	220*	180*
J-ring flow at 10 minutes, mm	600	580	600	690	690	660	600	660	625	605	620	0	0
J-ring flow at 40 minutes, mm	580	610	580	700	690	670	580	695	570	550	600	0	0
h_2/h_1 L box at 10 minutes	0.06	0.05	0.43	0.64	0.70	0.60	0.63	0.56	0.68	0.64	0.58	0	0
h_2/h_1 L box at 40 minutes	0.02	0.12	0.40	0.68	0.58	0.63	0.50	0.63	0.58	0.48	0.45	0	0
Filling capacity at 10 minutes, %	51	48	74	100	92.9	88	88	88	83	86	79	0	0
Filling capacity at 40 minutes, %	50	57	74	90	94.5	94	70	91	81	85	75	0	0
Unit weight at 10 minutes, kg/m^3	2433	2440	2410	2430	2415	2373	2362	2398	2342	2360	2398	2456	2518
Unit weight at 40 minutes, kg/m^3	2433	2465	2438	2446	2400	2410	2390	2406	2397	2380	2406	2494	2527
Air volume at 10 minutes, %	1.7	2.2	2.8	0.7	1.8	2.3	0.7	0.9	3.8	3.7	3.9	1.6	1.8
Air volume at 40 minutes, %	1.8	1.7	2.7	0.68	2.0	1.7	0.4	0.8	2.2	3.9	3.5	1.3	1.7
Maximum surface settlement, %	0.28	0.50	0.32	0.54	0.50	0.43	0.47	0.30	0.30	0.32	0.28	0.12	0.41
Dynamic yield stress at 10 minutes, Pa	110	88	83	83	93	82	117	180	101	83	121	347	315
Dynamic yield stress at 40 minutes, Pa	129	64	88	84	91	72	213	116	135	128	142	345	302
Plastic viscosity at 10 minutes, Pa-sec	1154	1528	500	266	108	171	80	83	130	141	135	1605	159

Table 5. Properties of SCC and HPC mixtures investigated in phase 1 (contd.)

w/cm binder content-HRWRA type-(SF or FA)	SCC1 28-450-NS-FA	SCC2 28-450-HES-SF	SCC3 28-550-NS-SF	SCC4 28-550-HES-FA	SCC5 38-450-NS-SF	SCC6 38-450-HES-FA	SCC7 38-550-NS-FA	SCC8 38-550-HES-SF	SCC9 33-500-NS-SF	SCC10 33-500-NS-SF	SCC11 33-500-NS-SF	HPC1	HPC2
Plastic viscosity at 40 minutes, Pa-sec	955	1520	621	313	96	119	52	81	154	118	149	1052	155
18-hour f'_c steam cured, MPa	38.9	59.3	56.8	34.1	33.6	30.9	26.9	50.0	51.5	47.8	50.0	64.2	23.5
18-hour f'_c air cured, MPa	3.1	31.3	25.3	19.1	18.0	20.1	17.6	29.0	25.5	27.5	29.3	50.8	23.8
28-day f'_c, MPa	71.1	84.4	89.9	56.3	56.3	54.4	52.7	68.7	82.2	80.6	82.0	83.0	48.8
56-day f'_c, MPa	82.8	90.8	90.4	64	62.9	64.1	62.5	70.9	84.3	81.8	87.0	91.4	52.2
18-hour E_c steam cured, GPa	34.5	40.5	37.5	30.5	31.0	26.5	25.5	32.0	34.5	35.0	34.5	40.5	28.0
56-day E_c moist cured, GPa	44.5	45.0	43.0	36.5	39.5	38.0	39.0	38.0	41.5	40.0	39.5	44.0	37.5

* Slump

Note: E_c = modulus of elasticity of concrete; f'_c = compressive strength of concrete; FA = fly ash; h_1 = height of SCC remaining in the vertical section (L-box test); h_2 = height of SCC at leading edge of apparatus (L-box test); HES = high-early-strength; HRWRA = high-range water-reducing admixture; SCC = self-consolidating concrete; SF = silica fume; *w/cm* = water–cementitious material ratio, by mass. 1 mm = 0.0394 in.; 1 Pa = 0.000145 psi; 1 MPa = 0.145 ksi; 1 GPa = 145 ksi; 1 kg/m^3 = 1.685 lb/yd^3.

those prepared with the same cement and 20% Class F fly ash. The binder type does not seem to have any significant influence on workability for the range of parameters used in this investigation. Therefore, the use of a relatively low *w/cm* (0.28) and high binder content of 550 kg/m^3 (930 lb/yd^3) is required for SCC with a 56-day design compressive strength of 11,600 psi (80 MPa) with adequate workability. In addition, the combination of Type GU cement and 7% silica fume is recommended for such high-strength concrete.

For the concrete with a 56-day design compressive strength of 60 MPa (8700 psi), the use of a relatively high *w/cm* of 0.38 and lower binder content of 450 kg/m^3 (760 lb/yd^3) with 20% fly ash was selected. The lower binder content in the concrete proportioned with a *w/cm* of 0.38 is favored to limit the paste volume, thus leading to lower shrinkage and creep.

The HES-type HRWRA is selected to secure better passing ability and shorter setting time than the NS-type HRWRA. Both HRWRA types resulted in adequate workability retention for the intended use. In addition, the HES-type HRWRA is recommended in case of SCC subjected to ambient temperature curing (air curing) to secure adequate mechanical properties at 18 hours.

Effect of steam-curing parameters on mechanical properties

SCC1 and SCC2 mixtures designed to secure 56-day compressive strengths of 80 and 60 MPa (11,600 and 8700 psi), respectively, were used in this investigation. The mixtures were used to evaluate the effect of steam-curing parameters on mechanical properties at release time (18 hours). **Table 9** presents mechanical properties of SCC1 and SCC2 mixtures subjected to various steam-curing regimes.

The SCC1 mixture (28-550-NS-SF) was subjected to eight different steam-curing regimes. Four steam-curing regimes were applied to the SCC2 mixture (38-450-HES-FA). The coded values of the mixture parameters can be expressed as follows:

- coded maximum chamber temperature = (absolute maximum chamber temperature – 55°C)/5
- coded rate of heating = (absolute rate of heating – 17C°/hr)/5
- coded preset period = (absolute preset period – 3.5 hr)/1.5

Table 6. Derived equations to model the effect of mixture parameters on properties of fresh concrete

	Modeled response	Derived equations	R^2
	HRWRA demand, L/m^3	6.8 – 4.1(*w/cm*) – 1.3(BC) + 1.3(BT) + 1.08(*w/cm*)(BC)	0.94
	T-50 time, sec	13.5 – 11. 9(*w/cm*) – 6.9 BC) + 5.9(*w/cm*)(BC)	0.97
Passing ability	J-ring flow	635 +17.5(*w/cm*) + 12.5(SPT) – 25(*w/cm*)(BC) + 25(*w/cm*)(BT)	0.98
	L-box blocking ratio (h_2/h_1)		0.94
Filling capacity	Caisson filling capacity, %	78.7 + 10.5(*w/cm*) + 8.8(BC) – 10.0(*w/cm*)(BC) + 4.2(*w/cm*)(BT)	0.92
	Slump flow: J-ring flow, mm	38.12 – 18.13(*w/cm*) – 14.37(SPT) + 18.1(*w/cm*)(BC) – 20.3(*w/cm*)(BT)	0.99
Stability	Surface settlement, %	0.42 + 0.025(SPT) – 0.03(*w/cm*)(BC) – 0.085(*w/cm*)(SPT)	0.96
Rheology	Plastic viscosity (Pa-sec)	486.3 – 375.6(*w/cm*) – 254(BC) + 225(*w/cm*)(BC)	0.99

Note: BC = binder content; BT = binder type; HRWRA = high-range water-reducing admixture; R^2 = correlation coefficient; SPT = type of high-range water-reducing admixture used; *w/cm* = water–cementitious material ratio, by mass. 1 mm = 0.0394 in.; 1 Pa = 0.000145 psi; 1 L/m^3 = 7.475 × 10^{-3} gal./ft^3.

Table 7. Derived equations to model the effect of mixture parameters on mechanical properties

Property	Age	Derived equations	R^2
f'_c, MPa	18-hour steam cured	41.3 + 8.6(BT) – 5.7(*w/cm*) + 2.8(*w/cm*)(SPT)	0.91
	18-hour air cured	20.4 + 5.5(BT) + 4.4(SPT) + 2.3(BC) – 3.1(*w/cm*)(BT)	0.98
	28 days	66.7 – 8.7(*w/cm*) + 8.1(BT) + 4.3(*w/cm*)(SPT) – 3.6(*w/cm*)(BT)	0.99
	56 days	73.6 – 8.5(*w/cm*) + 5.2(BT) + 3.5(*w/cm*)(SPT) – 3.4(*w/cm*)(BT) + 3.2(*w/cm*)(BC)	0.97
E_c, GPa	18 hours	32.3 – 3.5(*w/cm*) + 3.0(BT) + 0.9(*w/cm*)(BC)	0.99
	56 days	40.4 – 1.8(*w/cm*) – 1.3(BC) – 1.1(SPT) + 1.2(*w/cm*)(BC)	0.90

Note: BC = binder content; BT = binder type; E_c = modulus of elasticity of concrete; f'_c = compressive strength of concrete; R^2 = correlation coefficient; SPT = type of high-range water-reducing admixture used; *w/cm* = water–cementitious material ratio, by mass. 1 MPa = 145 psi; 1 GPa = 145 ksi.

The derived statistical models (**Table 10**) rank the steam-curing parameters affecting early-age mechanical properties for SCC1. All factors are expressed in coded values. A negative estimate indicates that an increase in the modeled factor can lead to a reduction in the measured response. High R^2 values are obtained for the various modeled responses.

Maximum chamber temperature For the majority of the derived statistical models, the maximum chamber temperature had the most significant effect on the mechanical properties of steam-cured SCC1. The increase in maximum chamber temperature from 50°C to 60°C (122°F to 140°F) led to significantly higher 18-hour compressive strengths. On average, concrete subjected to a higher chamber temperature of 60°C (140°F) exhibited 10% higher 18-hour compressive strengths than did concrete subjected to 50°C (122°F) maximum chamber temperature. Mixtures with chamber temperature of 60°C (140°F) exhibited higher ratios of 18-hour steam-cured to 28-day moist-cured compressive strength. **Figure 1** shows the cube diagram of compressive strength ratios between 18-hour steam-cured and 28-day moist-cured values. On average, SCC1 with a 56-day f'_c of 80 MPa (11,600 psi) developed 63% of the 28-day moist-cured strength after 18 hours of steam curing. The relative strength increases with the maximum chamber temperature, as presented in Fig. 1.

Maximum chamber temperature does not seem to have a major effect on E_c. However, for a given rate of heating and preset period, the increase in maximum chamber temperature slightly reduced the 18-hour E_c. This may be in part due to damage in the interfacial transition zone between aggregate and cement paste resulting from a dramatic temperature increase during a short period.

Rate of heating In general, increasing the rate of heating from 12C°/hr to 22C°/hr (22F°/hr to 40F°/hr) slightly increased the 18-hour f'_c. On average, for a given maxi-

Table 8. Recommendations for proportioning C60 MPa and C80 MPa SCC

	w/cm	Binder content, kg/m³	HRWRA type	Binder type
HRWRA demand*	0.38	550	n/a	GU + FA
J-ring	0.38	n/a	HES PCE	n/a
Slump flow: J-ring flow*	0.38	n/a	HES PCE	n/a
T-50*	0.38	550	n/a	n/a
L-box blocking ratio, h_2/h_1	0.38	550	n/a	n/a
Caisson filling capacity	0.38	550	n/a	n/a
Plastic viscosity*	0.38	n/a	HES PCE	n/a
18-hour f'_c steam cured	0.28	n/a	n/a	GU + SF
18-hour f'_c air cured	n/a	550	HES PCE	GU + SF
18-hour E_c steam cured	0.28	n/a	n/a	GU + SF
28-day f'_c moist cured	0.28	n/a	n/a	GU + SF
56-day f'_c moist cured	0.28	n/a	n/a	GU + SF
56-day E_c moist cured	0.28	450	NS PCE	n/a

* Lower values indicate better performance

Note: E_c = modulus of elasticity of concrete; f'_c = compressive strength of concrete; FA = Class F fly ash; GU = general use; HES = high-early-strength; HRWRA = high-range water-reducing admixture; n/a = not applicable; NS = normalstrength; PCE = polycarboxylate ether-based HRWRA; SCC = self-consolidating concrete; SF = silica fume; *w/cm* = water–cementitious material ratio, by mass. 1 kg/m³ = 1.685 lb/yd³; 1 MPa = 145 psi.

Table 9. Mechanical properties of SCC1 mixtures, steam-curing optimization, phase 2

Mechanical properties	Mixture type and batch number										
	SCC1								SCC1 central point		
	1	2	3	4	5	6	7	8	9	10	11
18-hour f'_c steam cured, MPa	49.5	52.5	52.3	51.2	53.6	55.1	55.9	60.4	54.2	53.4	54.9
18-hour f'_c air cured, MPa	11.6	8.3	11.7	9.5	12.5	10.3	10.2	6.0	8.7	4.9	5.3
7-day f'_c, MPa	74.2	73.1	68.5	69.6	75.9	67.1	78.1	71.3	66.0	70.9	72.0
28-da f'_c, MPa	75.6	86.1	88.5	86.3	88.0	87.1	84.8	85.5	78.1	81.8	89.6
56-day f'_c, MPa	86.4	90.6	88.8	88.4	92.5	87.5	93.7	93.3	82.2	90.0	88.2
18-hour E_c steam cured, GPa	38.0	42.5	38.0	37.5	37.0	36.5	39.5	37.0	38.0	38.0	37.0
56-day E_c moist cured, GPa	43.0	43.0	42.5	43.5	44.0	41.0	44.0	44.0	43.0	44.0	42.0

Note: E_c = modulus of elasticity of concrete; f'_c = compressive strength of concrete; SCC = self-consolidating concrete.
1 MPa = 145 psi; 1 GPa = 145 ksi.

mum chamber temperature and preset period, concretes subjected to a heating rate of 22C°/hr (40F°/hr) exhibited 5% higher 18-hour compressive strengths than those subjected to the lower heating rate of 12C°/hr (22F°/hr).

The rate of heating did not significantly affect the 18-hour E_c. However, the influence of the heating rate on 18-hour E_c varied with the maximum chamber temperature and preset period. For a maximum chamber temperature of 60°C (140°F), an increase in the rate of heating increased the 18-hour E_c. Conversely, for a chamber temperature of 50°C (122°F), mixtures subjected to the higher rate of heating of 22C°/hr (40F°/hr) exhibited slightly lower E_c at 18 hours than did those subjected to the lower heating rate of 12C°/hr (22F°/hr).

Table 10. Derived equations to model the effect of steam-curing parameters on mechanical properties of SCC1

Modeled response	Derived equations	R^2
18-hour steam-cured compressive strength, MPa	54 + 2.4(MCT) + 1.2(RH) + 0.9(PP)	0.89
18-hour steam-cured compressive strength/28-day moist-cured compressive strength	0.63 + 0.028(MCT) + 0.014(RH) + 0.011(PP)	0.89
18-hour steam-cured compressive strength/18-hour air-cured compressive strength	6.0 + 0.26(MCT) + 0.13(RH) + 0.10(PP)	0.89
18-hour steam-cured E_c, GPa	38 – 0.7(MCT) + 1(MCT)(RH) – 0.87(MCT)(PP) – 0.87(RH)(PP)	0.97

Note: E_c = modulus of elasticity of concrete; MCT = maximum chamber temperature; PP = preset period; R^2 = correlation coefficient; RH = rate of heating; SCC = self-consolidating concrete. 1 MPa = 145 psi; 1 GPa = 145 ksi.

Preset period The effect of the preset period varied with the applied maximum chamber temperature. In the case of a maximum chamber temperature of 60°C (140°F), all mixtures subjected to a preset period of 5 hours developed higher 18-hour steam-cured compressive strengths than those with a 2-hour preset period. This is not the case with a maximum chamber temperature of 50°C (122°F), where similar 18-hour compressive strengths were achieved regardless of the preset period. Statistical analysis revealed that the preset period does not have a major influence on E_c determined at 18 hours. Nevertheless, the effect of the preset period on 18-hour E_c also varied with the maximum chamber temperature and rate of heating.

As presented in **Table 11**, statistical models were also established for SCC2 designed to achieve a 56-day f_c' of 60 MPa (8700 psi). Probability values less than 0.1 (confidence limit of 90%) are considered strong evidence that the parameter had a significant effect on the modeled responses. None of the derived models was qualified in the confidence limit of 90% because probability values were higher than 0.1, indicating that the steam-curing parameters do not have a significant effect on the 18-hour f_c' and E_c of SCC2. Therefore, optimization of the steam-curing regime for SCC with the lower design strength of 60 MPa is less critical than for SCC1. In addition, SCC2 subjected to air curing at 23°C ± 2°C (73.4°F ± 3.6°F) with a relative humidity of 50% developed similar mechanical proper-

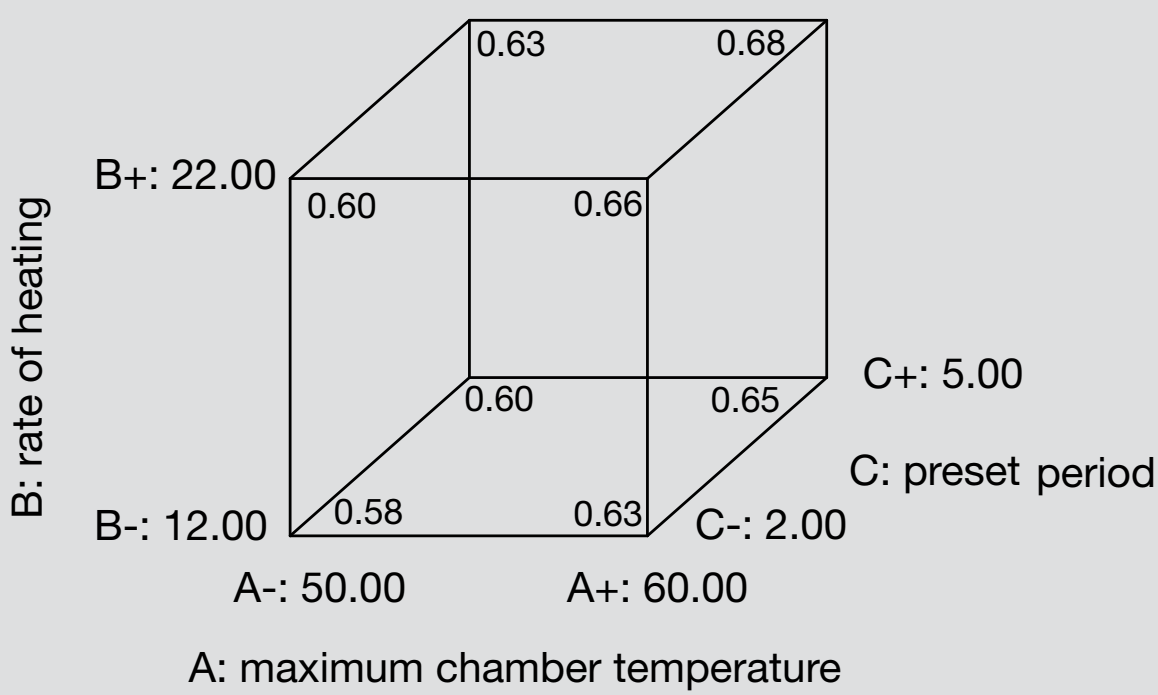

Figure 1. Three-dimensional cube diagram of compressive strength ratio of 18-hour steam-cured strength to 28-day moist-cured strength for SCC1.
Note: SCC = self-consolidating concrete.

Table 11. Derived statistical models for mechanical properties of SCC2

Modeled response	Derived equations	R^2	Probability > F*
18-hour steam-cured compressive strength, MPa	31 + 2.2 (PP) + 1.0 (MCT)	0.98	0.20 (not acceptable)
18-hour steam-cured compressive strength/28-day moist-cured compressive strength	0.54 + 0.038(PP) + 0.019(MCT)	0.98	0.13 (not acceptable)
18-hour steam-cured compressive strength/18-hour air-cured compressive strength	1.1 + 0.076(PP) + 0.036(PP)	0.98	0.20 (not acceptable)
18-hour steam cured E_c, GPa	28 – 1.3(MCT) + 0.5(PP)	0.97	0.13 (not acceptable)

*Probability values less than 0.1 (confidence limit of 90%) are considered strong evidence that the studied parameter had a significant impact on the modeled responses. None of the derived models were qualified in the confidence limit of 90% because probability values were higher than 0.1.
Note: E_c = modulus of elasticity of concrete; F = Fisher-Snedecor distribution function; MCT = maximum chamber temperature; PP = preset period; R^2 = correlation coefficient; SCC = self-consolidating concrete. 1 MPa = 145 psi; 1 GPa = 145 ksi.

ties at 18 hours to those of steam-cured concrete. Thus, for SCC with a 56-day design compressive strength of 60 MPa, the selection of an HRWRA or binder composition that can promote early-age strength development can well be sufficient, instead of using steam curing.

Comparison of mechanical properties of HPC and SCC

Two HPC mixtures were subjected to a steam-curing regime with a maximum chamber temperature of 60°C (140°F), a heating rate of 22°C/hr (40°F/hr), and a preset period of 5 hours. HPC1 and HPC2 have 56-day design compressive strengths of 80 and 60 MPa (11,600 and 8700 psi), respectively. The HPC1 mixture exhibited a significantly lower 18-hour steam-cured to 18-hour air-cured compressive strength ratio compared with the average ratio for SCC1 (1.26 versus 5.3). This is due to the higher HRWRA dosage of SCC1, thus leading to retardation in strength gain at ambient temperatures. Thus, the steam-curing parameters are more critical for the strength development of high-strength SCC than for HPC mixtures. Similarly, the HPC2 mixture designed for a 56-day compressive strength of 60 MPa was also subjected to the same steam-curing regime as HPC1. As in the case of SCC2 with a 56-day design compressive strength of 60 MPa, the steam-curing process did not lead to a significant increase in the 18-hour compressive strength and elastic modulus of HPC2.

Recommendations for steam curing

Table 12 summarizes recommendations for steam-curing parameters for SCC with a design compressive strength of 80 MPa (11,600 psi). SCC mixtures steam cured with a higher maximum chamber temperature of 60°C (140°F) developed significantly greater 18-hour compressive strength. Therefore, the use of the higher maximum chamber temperature of 60°C is recommended to accelerate early-age strength development. As presented in Table 12, mixtures steam cured with a higher heating rate of 22°C/hr (40°F/hr) and a longer preset period of 5 hours exhibited higher 18-hour compressive strengths compared with those prepared with the lower heating rate of 12°C/hr (22°F/hr) and a shorter preset period of 2 hours. The effect of the rate of heating and preset period on 18-hour E_c varies with the maximum chamber temperature. Therefore, the optimum rate of heating and preset period should be selected based on the maximum chamber temperature in use in order to secure an adequate level of compressive strength and elastic modulus. It is important to point out that the high-early-age-strength type HRWRA should be used for concrete subjected to ambient-temperature curing (air curing) to accelerate strength development of the concrete. On the other hand, in the case of SCC subjected to steam curing, the effect of the HRWRA type on the strength gain is marginal.

Conclusion

Based on the results reported here, the following conclusions are warranted:

- Steam curing presents an efficient method of gaining early-age compressive strength for SCC with a design compressive strength of 80 MPa (11,600 psi). By means of steam curing, such concrete can develop six times higher compressive strength at 18 hours than the same concrete subjected to ambient-temperature curing at 23°C ± 2°C (73.4°F ± 3.6°F). The early-age strength gain by the use of an HES type HRWRA is larger for air-cured concrete than for steam-cured SCC.

- In the case of HPC and SCC with design compressive strengths of 60 MPa (8700 psi), steam curing did not significantly improve the 18-hour compressive strength. That is, mixture proportions that promote early strength development may obviate the need for steam curing.

Table 12. Recommendations for steam-curing parameters for 80 MPa SCC

Response	Modeled parameter		
	Maximum chamber temperature, °C*	Rate of heating, °C/hr†	Preset period, hours‡
18-hour steam-cured compressive strength	60	22	5
18-hour steam-cured compressive strength/28-day moist-cured compressive strength	60	22	5
18-hour steam-cured compressive strength/18-hour air-cured compressive strength	60	22	5
18-hour steam-cured E_c	50	No recommendation	No recommendation

*Based on performance under two options: 50°C or 60°C.
†Based on performance under two options: 12°C/hr or 22°C/hr.
‡Based on performance under two options: 2 hours or 5 hours.
Note: Rate of cooling = 15°C/hr. E_c = modulus of elasticity of concrete; SCC = self-consolidating concrete. 1 MPa = 145 psi; °C = (°F – 32)/1.8.

- Maximum chamber temperature was shown to have the most significant effect on the 18hour steam-cured compressive strength and modulus of elasticity, followed by the rate of heating and preset period.

- In the case of SCC with an 80 MPa (11,600 psi) design compressive strength, a high maximum chamber temperature of 60°C (140°F) with a high rate of heating of 22C°/hr (40F°/hr) and a long preset period of 5 hours is recommended to accelerate early-age strength.

- For a given maximum chamber temperature and preset period, concrete mixtures subjected to a higher rate of heating of 22C°/hr (40F°/hr) can develop higher 18-hour compressive strengths than those subjected to a lower heating rate of 12C°/hr (22F°/hr).

- The effect of the rate of heating and the preset period on the 18-hour elastic modulus varies with the maximum chamber temperature. Therefore, the optimum rate of heating and preset period should be selected based on the maximum chamber temperature in use to secure the desired compressive strength and elastic modulus.

Future work

The total curing heat input (amount of energy) associated with the different preset periods, the different rates of heating, and the different lengths of time being held at maximum temperature and cooling rate can be depicted using a maturity concept to evaluate the effect of steam-curing parameters on the early-age gain of mechanical properties of concrete. Further investigation on the maturity concept related to the steam-curing process is needed to estimate the minimum amount of energy required to secure the target compressive strength of SCC. In addition, an investigation regarding the influence of curing temperature higher than 60°C (140°F) on the mechanical properties and durability aspects of SCC is required.

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Notation

E_c = modulus of elasticity of concrete

f_c' = compressive strength of concrete

h_1 = height of self-consolidating concrete remaining in the vertical section (L-box test)

h_2 = height of self-consolidating concrete at leading edge of apparatus (L-box test)

MCT = maximum chamber temperature

PP = preset period

RH = rate of heating

w/cm = water–cementitious material ratio, by mass

R^2 = correlation coefficient

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Abstract

Steam curing is often used in precast concrete manufacturing plants to accelerate strength gains. The mechanical properties of steam-cured concrete are affected by mixture composition and can vary widely with steam-curing parameters. The main objective of the study reported in this paper is to optimize the steam-curing regime of high-strength self-consolidating concrete (SCC). Test parameters included the preset period, the maximum chamber temperature, and the rate of heating. Two SCC mixtures were optimized to secure design compressive strengths of 8700 and 11,600 psi (60 and 80 MPa). The mixtures were prepared with a water–cementitious materials ratio of 0.38 and 0.28, respectively. The maximum chamber temperature was shown to have a dominant effect on the 18-hour compressive strength. The preset period also exhibited significant influence on compressive strength and elastic modulus. For a given maximum chamber temperature of 140°F (60°C), an increase in preset period from 2 to 5 hours resulted in a 5% increase in early-age strength.

Keywords

Modulus of elasticity, SCC, self-consolidating concrete, steam curing, strength.

Review policy

This paper was reviewed in accordance with the Precast/Prestressed Concrete Institute's peer-review process.

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