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Creep behaviour of normal- and high-strength self-compacting concrete

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Abstract. Realistic prediction of concrete creep is of crucial importance for durability and long-term serviceability of concrete structures. To date, research about the behaviour of self-compacting concrete (SCC) members, especially concerning the long-term performance, is rather limited. SCC is quite different from conventional concrete (CC) in mixture proportions and applied materials, particularly in the presence of aggregate which is limited. Hence, the realistic prediction of creep strains in SCC is an important requirement for the design process of this type of concrete structures. This study reviews the accuracy of the conventional concrete (CC) creep prediction models proposed by the international codes of practice, including: CEB-FIP (1990), ACI 209R (1997), Eurocode 2 (2001), JSCE (2002), AASHTO (2004), AASHTO (2007), AS 3600 (2009). Also, SCC creep prediction models proposed by Poppe and De Schutter (2005), Larson (2007) and Cordoba (2007) are reviewed. Further, new creep prediction model based on the comprehensive analysis on both of the available models i.e. the CC and the SCC is proposed. The predicted creep strains are compared with the actual measured creep strains in 55 mixtures of SCC and 16 mixtures of CC.

Keywords: self-compacting concrete (SCC); conventional concrete (CC); creep; long-term behaviour

1. Introduction

Self-compacting concrete (SCC) basically consists of the same components as conventional concrete (CC) (cement, water, aggregates, admixtures, and mineral additions), but the final composition of the mixture and its fresh characteristics are different. In comparison with the CC, the SCC contains larger quantities of mineral fillers such as finely crushed limestone or fly ash, higher quantities of high-range water-reducing admixtures, and the maximum size of the coarse aggregate is smaller. These modifications in the composition of the mixture affect the behaviour of the concrete in its hardened state, including the creep and the shrinkage deformations (Aslani 2014, Aslani and Nejadi 2012a, b). Creep depends on the characteristics of aggregate stiffness and texture, w/c ratio, volume of paste, volume of coarse aggregate, cement type, admixture type, curing method, ratio of volume to surface area, environmental conditions, magnitude of loads, and age of first loading. According to Neville (1996) mostly the hydrated cement paste experiences

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creep, while the aggregate is the only portion which resists against creep. Therefore, creep is highly dependent on the stiffness of the chosen aggregate and its proportion within the mixture (Neville 1996). As a result, since creep mainly occurs in the cement paste, main concern arises that SCC may exhibit higher creep because of its high paste content.

Because the SCC has a higher paste volume (or higher sand to aggregate ratio) to achieve high workability and high early strength, several researchers have reported relatively large creep strains of SCC for precast, prestressed concrete, resulting in larger prestress losses (Issa *et al.* 2005, Naito *et al.* 2006, Schindler *et al.* 2007, Suksawang *et al.* 2006). Although mechanical properties of the SCC are superior to those of the CC, creep of SCC is significantly high (Issa *et al*. 2005). Naito *et al.* (2006) also found that the SCC exhibits higher creep than the CC, which is due to the high fine aggregate volume in the SCC. Naito *et al.* (2006) found that the creep coefficient of the SCC and the CC was 40 and 6 percent higher than the ACI 209 (1992) prediction model, respectively (Aslani and Nejadi 2012c, d, e, Aslani 2013).

Different methodology followed to obtain SCC in different countries (Ouchi *et al.* 2003) and limited number of studies are available concerning its long-term behaviour (Persson 2001, 2005, Poppe and De Shutter 2001, Seng and Shima 2005, Mazzotti *et al.* 2006). It is not clear in the available studies if current international standards apply successfully for the SCC (Klug and Holschemaker 2003, Vidal *et al.* 2005, Landsberger and Gomez 2007). Moreover, it is not assessed if long-term properties can be predicted with reference to conventional mechanical and physical parameters only (like strength, w/c, etc) or the adoption of parameters concerning the mix design is needed (Aslani and Nejadi 2013a, b).

2. Research significance

The objectives of the present research are:

(a) To establish an experimental results database of creep.

(b) To review the accuracy of the CC creep prediction models proposed by international codes of practice, including: CEB-FIP (1990), ACI 209R (1997), Eurocode 2 (2001), JSCE (2002), AASHTO (2004), AASHTO (2007) and AS 3600 (2009).

(c) To review the accuracy of the SCC creep prediction models proposed by Poppe and De Schutter (2005), Larson (2007) and Cordoba (2007).

(d) To propose a new prediction creep model based on the comprehensive analysis of the available models and the experimental results database of both the CC and the SCC.

3. Creep experimental results database

The use of a database with experimental results from various published investigations is an important tool for studying the applicability of the various creep estimation models of the SCC. To apply the models to a particular concrete mixture, it is necessary to use only investigations that adequately define the applied testing methodology. The presented experimental results in the database are mainly from the papers presented at the various conferences on the SCC and other published articles. Using experimental data results from different sources can frequently be problematic for the following reasons: 1. there is often insufficient information regarding the exact composition of the concrete mixtures; 2. the size of the specimen, curing condition, and the testing methodology vary between the different investigations and in some cases this information is not fully described; 3. in many cases it is difficult to extract the relevant experimental values because the published results are incomplete or are presented in graphical form and the data values have to be extrapolated.

Tables 1-2 present a general summary of the concrete mixtures included in the database. The database comprises test results from 11 different investigations, with a total of 55 SCC and 16 CC mixtures for creep tests. Table 1 also includes complimentary information regarding the applied stress to the creep specimens, final age of the concrete (in days), relative humidity (RH), type of the specimen, type of the cement and the filler. Table 2 includes information about cement content, water, compressive strength and cement to powder (c/p) ratio for each mixtures that have been used in the different investigation. Figs. 1 and 2 show the CC and SCC experimental results database that is summarized in Table 1 (creep coefficient versus time in days) (Aslani and Maia, 2013; Aslani and Natoori, 2013). By considering experimental results of creep in the database the following conclusions are observed:

(1) by decreasing of the water to binder ratio, increase in the creep strains is observed,

(2) increase in the proportion of the total aggregate in the mixture could cause decrease in the total creep,

(3) when the content of total aggregate and binder in concrete is held constant, the total creep decreases as coarse aggregate proportion increases.

Table 1 Creep experimental results database

Reference	No. of SCC mixtures	No. of CC mixtures	Applied stress to the creep specimens	Final age of concrete (days)
Chopin *et al*. (2003)	5	1	40% or 60% of the compressive strength at 28 days	365
Poppe and De Schutter (2005)	6	0	1/3 of the compressive strength at 28 days	1400
Horta (2005)	6	0	40% of the compressive strength at 28 days	70, 200
Larson (2006)	1	0	40% of the compressive strength at 28 days	520
Turcry *et al.* (2006)	3	3	20% of the compressive strength at 7 days	65, 100
Cordoba (2007)	4	1	30% of the compressive strength at 28 days	365
Heirman *et al*. (2008)	7	1	±1/3 of the compressive strength at 28 days	70
Oliva and Cramer (2008)	11	4	40% of the compressive strength at 28 days	495
Kim (2008)	4	4	Changeable for each mixture	150
Zheng *et al*. (2009)	7	1	30% of the compressive strength at loading days	150
Loser and Leemann (2009)	1	1	Changeable for each mixture	91
Total of 71 mixtures	55	16		

Table 1 Continued

Reference	R.H. (%)	Type of specimen (mm)	Type of cement	Type of Filler
Chopin *et al*. (2003)	50	Cylinder (90×280)	CEM I	Limestone
Poppe and De Schutter (2005)	60	Prism (150×150×500)	CEM I 42.5 R, CEM I 52.5	Limestone
Horta (2005)	50	Cylinder (150×300)	CEM I , CEM III	Fly ash and GGBFS
Larson (2006)	50	Prism (101.6×101.6×609.6) and Cylinder (114.3×609.6)	CEM III	Limestone
Turcry *et al*. (2006)	50	Cylinder (110×200)	CEM I 52.5, CEM II 42.5	Limestone
Cordoba (2007)	50	Cylinder (101.6×203.2), (101.6×1057.8)	CEM I/II	Fly ash and GGBFS
Heirman *et al*. (2008)	60	Cylinder (120×300)	CEM I 42.5 R, CEM III/A 42.5 N LA	Limestone
Oliva and Cramer (2008)	50	Cylinder (152.4×213.6)	CEM I	GGBFS
Kim (2008)	50	Cylinder (100×200)	CEM III	Fly ash and Limestone
Zheng *et al*. (2009)	60	Prism (100×100×400)	CEM I	Fly ash
Loser and Leemann (2009)	70	Prism (120×120×360)	CEM I 42.5 N, CEM II/A-LL 45.2 N	Fly ash and Limestone

Table 2 Mix properties of the creep experimental database

Chopin *et al*. (2003)	Cement (kg/m^3)	Filler (kg/m^3)	c/p	w (kg/m^3)	f'_c (MPa)
SCC1	374	172	0.68	123	36.8
SCC2	344	256	0.57	131	36.5
SCC3	396	161	0.71	154	49.9
SCC4	396	177	0.69	115	36
SCC5	347	177	0.66	139	39.1
CC	348	-	1.00	132	35.6
Poppe and De Schutter (2005)	Cement (kg/m^3)	Filler (kg/m^3)	c/p	w (kg/m^3)	f'_c (MPa)
SCC1	300	300	0.50	165	59
SCC2	360	240	0.60	165	63.8
SCC3	400	200	0.67	165	73.7
SCC4	450	150	0.75	165	74.3
SCC5	360	240	0.60	165	66.6
SCC6	360	240	0.60	165	67.2
Horta(2005)	Cement (kg/m3)	Filler (kg/m3)	c/p	w (kg/m3)	$f'c$ (MPa)
S-Slag/Ash	427	172	0.71	182	73.3
G-Slag	433	133	0.77	208	56.6
Tindall	445	-	1.00	171	57.3
7N	468	99	0.83	177	87
7BL	461	97	0.83	181	77.7
67M	458	91	0.83	175	78.2

Table 2 Continued

Larson (2006)	Cement (kg/m3)	Filler (kg/m3)	c/p	*w* (kg/m3)	*f'c* (MPa)
SCC	446	-	1	224	51.7
CC	387	-	1	263	51.7
Turcry *et al.* (2006)	Cement (kg/m3)	Filler (kg/m3)	c/p	*w* (kg/m3)	*f'c* (MPa)
SCC1	330	110	0.75	180	40
SCC2	350	139	0.72	198	42
SCC3	350	150	0.70	187	48
CC1	280	-	1.00	170	37
CC2	350	-	1.00	175	41
CC3	360	-	1.00	170	53
Cordoba (2007)	Cement (kg/m3)	Filler (kg/m3)	c/p	*w* (kg/m3)	*f'c* (MPa)
KH	408	132.8	0.75	205.00	48.9
KM	418	136	0.75	210.00	48.2
CC	531	-	1	202.00	46.1
Heirman *et al.* (2008)	Cement (kg/m3)	Filler (kg/m3)	c/p	*w* (kg/m3)	*f'c*, cub150 (MPa)
SCC1	360	240	0.6	165	57.1
SCC3	360	240	0.6	165	69.2
SCC5	300	300	0.5	165	49
SCC14	360	240	0.6	144	68.4
SCC15	360	240	0.6	198	46.7
SCC16	360	240	0.6	165	73.3
SCC17	360	240	0.6	216	39.9
Kim (2008)	Cement (kg/m3)	Filler (kg/m3)	c/p	*w* (kg/m3)	*f'c* (MPa)
S5G-3	376	177	0.68	152	63
S7G-4,5,6	427	107	0.80	123	79
S5L-3	380	253	0.60	171	65
S7L-4,5,6	427	107	0.80	133	88
C5G	371	-	1.00	134	65
C7G	415	-	1.00	119	73
C5L	356	-	1.00	149	59
C7L	403	-	1.00	133	72
Zheng *et al.* (2009)	Cement (kg/m3)	Filler (kg/m3)	c/p	*w* (kg/m3)	*f'c* (MPa)
SCC1	440	110	0.80	180	52.6
SCC2	250	300	0.45	154	46.5
SCC3	288	192	0.60	145	47.7
SCC4	312	208	0.60	156	51
SCC5	330	220	0.60	165	52
SCC6	330	220	0.60	155	43.8
SCC7	330	220	0.60	165	40.5
CC	525	0	1.00	200	41.3
Loser and Leemann (2009)	Cement (kg/m3)	Filler (kg/m3)	c/p	w (kg/m3)	*f'c* (MPa)
SCC2	310	-	1	179	71.1
CC2	512	-	1	155	51.2

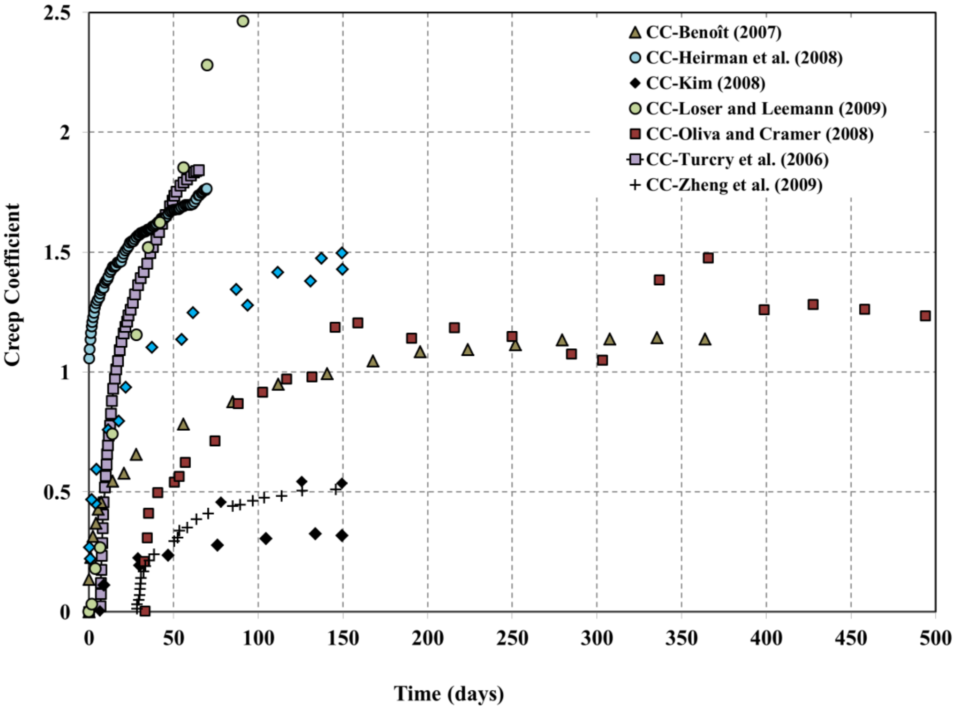

Fig. 1 Experimental database that summarized for CC (creep coefficient versus time (days))

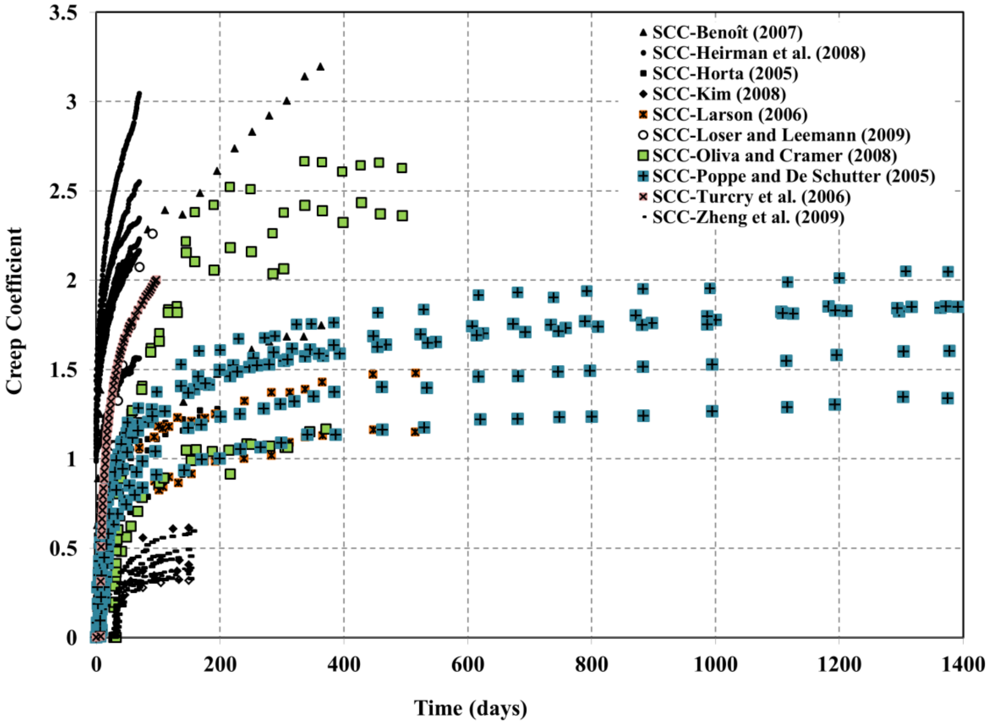

Fig. 2 Experimental database that summarized for SCC (creep coefficient versus time (days))

Table 3 Summary of the factors accounted for by different prediction models

	Models	CEB-FIP (1990)	ACI 209R (1997)	Eurocode 2 (2001)	JSCE (2002)	AASHTO (2004)	AASHTO (2007)	AS 3600 (2009)
Intrinsic Factors	Aggregate type							
	A/C ratio							
	Air content		■					■
	Cement content	■		■	■			
	Cement type							
	Concrete density		■					■
	Fine/Total aggregate ratio (mass)		■					■
	Slump		■					■
	W/C ratio				■			
	Water content				■			
Extrinsic Factors	Age at first loading	■	■	■	■	■	■	■
	Age of sample				■			
	Applied Stress	■	■	■	■			■
	Characteristic strength at loading							
	Cross-section shape				■			
	Curing conditions							
	Compressive strength at 28 days	■	■	■	■	■	■	■
	Duration of load	■	■	■	■			■
	Effective thickness	■	■	■	■	■	■	■
	Elastic modulus at age of loading							
	Elastic modulus at 28 days	■	■	■	■			■
	Relative humidity	■	■	■	■	■	■	■
	Temperature				■			
	Time drying commences							

4. Conventional concrete creep models

This paper assesses the accuracy of seven commonly used international code type models to predict creep strains without the need for creep tests. These empirical models, which vary widely in their techniques, require certain intrinsic and/or extrinsic variables, such as mix proportions, material properties and age of loading as input. The models considered are listed in Table 3, which also shows the factors required by each model (Aslani and Bastami 2014, Aslani *et al.* 2014a, b). In this study the accuracy of the creep prediction models proposed by the international codes of practice, including: CEB-FIP (1990), ACI 209R (1997), Eurocode 2 (2001), JSCE (2002), AASHTO (2004), AASHTO (2007), AS 3600 (2009) are compared with the actual measured creep strains in 52 mixtures of SCC and 15 mixtures of CC. Figs. 3-9 show comparison of the creep coefficient by available CC models with the experimental results available in the literature (Tables 1-2).

Table 4 Creep models for SCC

<table>
<tr><th>Ref.</th><th>Creep Prediction Models</th><th>Base Model</th></tr>
<tr><td>Poppe and De Schutter (2005)</td><td>$$\varepsilon_{cr}(t,t_0)=\frac{\sigma_c(t_0)}{E_{ci}}.\left[1+\frac{(1-(RH/RH_0))}{0.46(h/h_0)^{1/3}}\right].\frac{5.3}{(f_{cm}/f_{cm0})^{1/2}}\frac{1}{0.1+(t_0/t_1)^{0.2}}.$$ $$.\left[\frac{(t-t_0)/t_1}{\left(150\left(1+\left(1.2\frac{RH}{RH_0}\right)^{18}\right)\frac{h}{h_0}+250\right)+\frac{t-t_0}{t_1}}\right]^{0.3}.\left[\frac{1}{0.01+1.37(c/p)}\right]$$ Other symbols as in CEB-FIP (1990), c/p (cement to powder ratio)</td><td>CEB-FIP (1990)</td></tr>
<tr><td>Larson (2006)</td><td>For the specimens loaded at 1 day (for square and cylindrical specimens): $v_t=\frac{t^{0.7}}{16+t^{0.7}}(1.75)$
For the specimens loaded at 28 day (for square specimens): $v_t=\frac{t^{0.6}}{24+t^{0.6}}(2.00)$</td><td>ACI 209R (1997)</td></tr>
<tr><td>Cordoba (2007)</td><td>$$v_t=\frac{t^{\psi}}{d+t^{\psi}}v_u$$
<table>
<tr><th rowspan="2">Mixtures</th><th colspan="3">1 Year creep fit coefficients</th><th colspan="3">2 Year creep fit coefficients</th></tr>
<tr><th>ψ</th><th>$d\,(days)$</th><th>v_u</th><th>ψ</th><th>$d\,(days)$</th><th>v_u</th></tr>
<tr><td>KM</td><td>0.43</td><td>13.34</td><td>2.43</td><td>0.35</td><td>37.65</td><td>7.27</td></tr>
<tr><td>KH</td><td>0.44</td><td>16.95</td><td>5.08</td><td>N/A</td><td>N/A</td><td>N/A</td></tr>
<tr><td>REGULAR</td><td>0.39</td><td>8.22</td><td>1.25</td><td>N/A</td><td>8.54</td><td>1.31</td></tr>
<tr><td>Normal Values</td><td>0.4-0.8</td><td>6-30</td><td>1.3-4.15</td><td>0.4-0.8</td><td>6-30</td><td>1.3-4.15</td></tr>
</table></td><td>ACI 209R (1997)</td></tr>
</table>

5. Self-compacting concrete creep models

In Table 4 empirical models for calculating the creep of the SCC are shown. These models vary in complexity, and precision in the calculations. Figs. 10-12 show comparison of the creep coefficient by Poppe and De Schutter (2005), Larson (2006), Cordoba (2007) with the available creep coefficient experimental results.

6. Proposed self-compacting concrete creep model

The comparison of the different models and the experimental database shows that ACI 209R (1997), JSCE (2002), AASHTO (2004) models have conservative creep coefficient predictions. In this section, based on required certain intrinsic and/or extrinsic variables (i.e., mix proportions, material properties and age of loading) for the SCC mixtures are shown in Table 3. Table 3 shows that JSCE (2002) creep model gives a good coverage of the intrinsic and/or extrinsic variables that are useful for calculating the creep strain (Aslani and Samali 2014). Therefore, with the JSCE (2002) model as a basis, an attempt is made to formulate some proposals to include the c/p (cement to powder) ratio in order to obtain a better prediction of the time-dependent deformations of the normal strength and the high strength SCC. These proposed models are presented below in Eq. (1) to Eq. (10), for normal strength and high strength SCC:

For normal strength SCC with range of applicability: $45\% \leq RH \leq 80\%$; $130 \text{ kg/m}^3 \leq w \leq 230 \text{ kg/m}^3$; $100 \text{ mm} \leq v/w \leq 300 \text{ mm}$; $40\% \leq w/c \leq 65\%$; $f'_c(28) \leq 55$ MPa; $260 \text{ kg/m}^3 \leq c \leq 500 \text{ kg/m}^3$.

$$\varepsilon'_{cc}\left(t,t',t_0\right)=\sigma'_{cp}\times\varepsilon'_{cr}\ \left[1-\exp\left\{-0.09\ \left(t-t'\right)^{0.54}\right\}\right]\times\left(0.015+1.35\,(c/p)\right)^{-1}\quad \text{for c/p} < 0.65 \tag{1}$$

$$\varepsilon'_{cc}\left(t,t',t_0\right)=\sigma'_{cp}\times\varepsilon'_{cr}\ \left[1-exp\left\{-0.09\ \left(t-t'\right)^{0.54}\right\}\right]\times\left(0.015+1.05\,(c/p)\right)^{-1}\quad \text{for c/p} \geq 0.65 \tag{2}$$

$$\text{non-linear creep amplification function: } \sigma'_{cp}=\frac{\mu+\lambda.\sigma\left(t,t_0\right)^{\alpha}}{1-\kappa} \tag{3}$$

where μ and λ and α are additional parameters to be obtained from a least square minimization procedure starting from experimental data (Mazzotti and Ceccoli 2009) μ=0.90, λ=1.80, α=2.10; moreover, the stress function $\sigma(t, t_0)$ is the actual stress/strength ratio, being

$$\sigma\left(t,t_0\right)=\frac{\sigma\left(t_0\right)}{f_{cm}\left(t\right)} \tag{4}$$

in the case of constant applied load. In Eq. (3), numerator and denominator indicate the effect of sustained load and the effect of a damage level due to instantaneous loading. The law $f_{cm}(t)$ representing the evolution with time of compression strength has been defined by modifying MC90 proposal according to expression

$$f_{cm}\left(t\right)=f'_{c,28}.\exp\left[s'\left(1-\left(\frac{28}{t}\right)^{n}\right)\right] \tag{5}$$

where parameters s' and n have been specifically calibrated for each SCC concrete mix by using experimental results previously described. According to the available data, parameters s' and n range from 0.2-0.6, and 0.28-0.35, respectively (Mazzotti and Ceccoli 2009). The adoption of function $\sigma(t, t_0)$ allows for variable rate of increase of mechanical properties be taken into account, particularly important for concretes loaded at early ages. Finally, the non-linear behavior during the load application has been introduced in Eq. (3) according to the conventional scalar damage index $\kappa=1-E/E_0$, where E is the secant stiffness at the end of loading and E_0 is the initial tangent stiffness. Usually damage index κ is about 0.10-0.15 or 0.22-0.35 for low ($0.35f_{cm}(t)$) or medium ($0.55f_{cm}(t)$) applied stress levels, respectively.

$$\varepsilon'_{cr}=\varepsilon'_{bc}+\varepsilon'_{dc} \tag{6}$$

$$\varepsilon'_{bc}=\left[17.5\left(c+w\right)^{2.0}\left(w/c\right)^{2.4}\left\{ln\left(t'\right)\right\}^{-0.67}\right]\times10^{-10} \tag{7}$$

$$\varepsilon'_{dc}=\left[4500\left(w/c\right)^{4.2}\left(c+w\right)^{1.4}\left[\ln\left(\frac{v/s}{10}\right)\right]^{-2.2}\left\{1-\frac{RH}{100}\right\}^{0.36}t_0^{-0.30}\right]\times10^{-10} \tag{8}$$

For high strength SCC with range of applicability: $45\% \leq RH \leq 90\%$; $130 \text{ kg/m}^3 \leq w \leq 230 \text{ kg/m}^3$; $100 \text{ mm} \leq v/s \leq 300 \text{ mm}$; $40\% \leq w/c \leq 65\%$; $f'_c(28) \leq 80$ MPa; $260 \text{ kg/m}^3 \leq c \leq 500 \text{ kg/m}^3$.

$$\varepsilon'_{cc}\left(t,t',t_0\right)=\sigma'_{cp}\times\left[\frac{4w\left(1-RH/100\right)+350}{12+f'_c\left(t'\right)}\ ln\left(t-t'+1\right)\right]\times\left(10\times\left(c/p\right)^{0.678}\right)\quad \text{for c/p} < 0.65 \tag{9}$$

$$\varepsilon'_{cc}\left(t,t',t_0\right)=\sigma'_{cp}\times\left[\frac{4w\left(1-RH/100\right)+350}{12+f'_c\left(t'\right)}\ \ln\left(t-t'+1\right)\right]\times\left(13\times\left(c/p\right)^{0.701}\right)\quad \text{for c/p} \geq 0.65 \tag{10}$$

where t_0, t' and t are the effective age (days) of concrete at the beginning of drying, at the beginning of loading, and during loading respectively; ε'_{cr} is the final value of creep strain per unit stress; ε'_{bc} is the final value of basic creep strain per unit stress; ε'_{dc} is the final value of drying creep strain per unit stress.

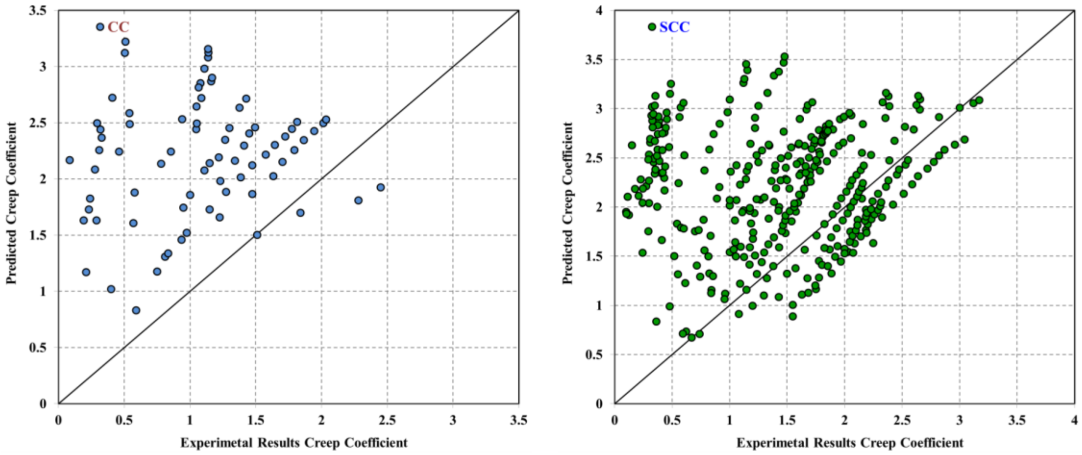

Fig. 3 Comparison of the CC and SCC creep coefficient from experimental results versus calculated values from CEB-FIP (1990) model

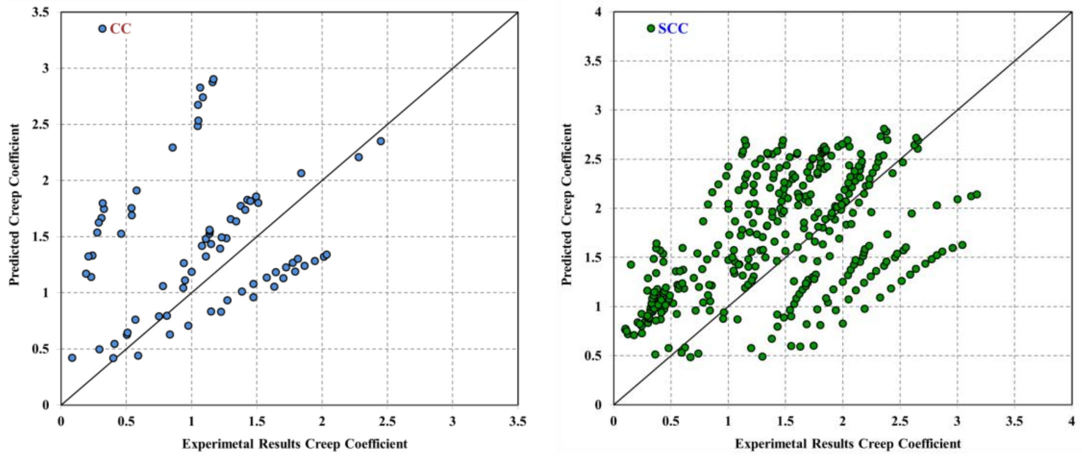

Fig. 4 Comparison of the CC and SCC creep coefficient from experimental results versus calculated values from ACI 209R (1997) model

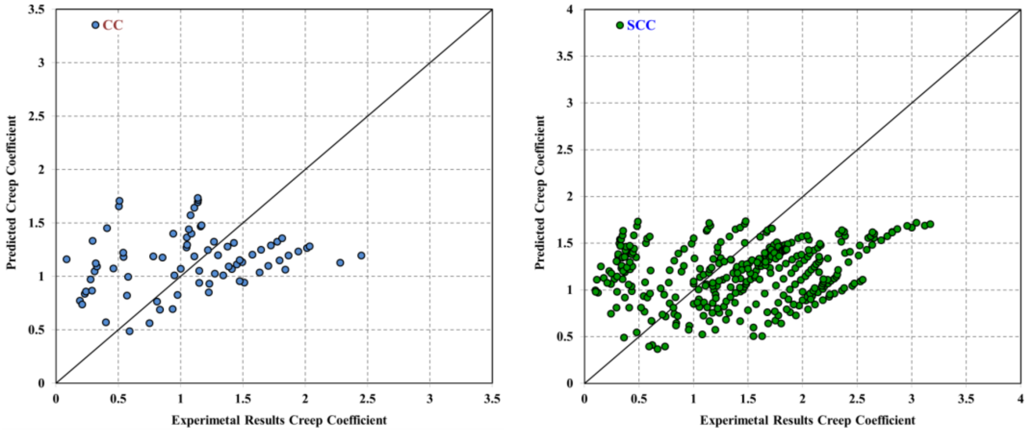

Fig. 5 Comparison of the CC and SCC creep coefficient from experimental results versus calculated values from Eurocode 2 (2001) model

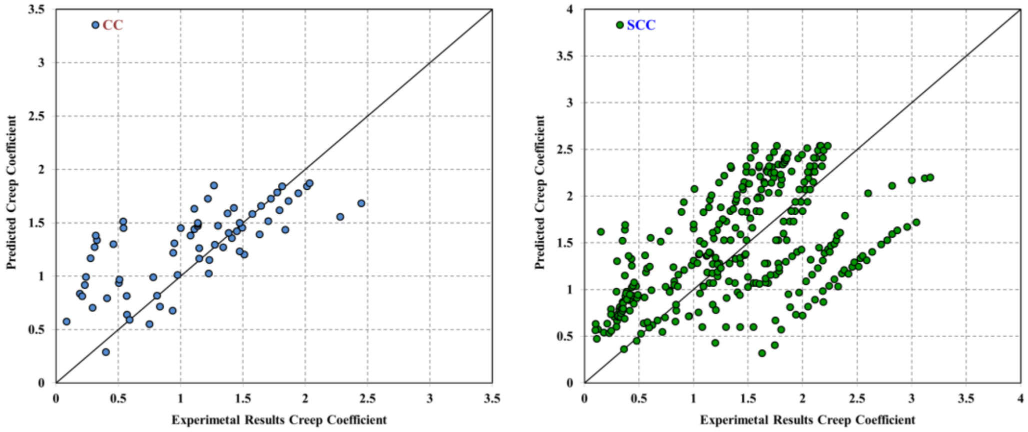

Fig. 6 Comparison of the CC and SCC creep coefficient from experimental results versus calculated values from JSCE (2002) model

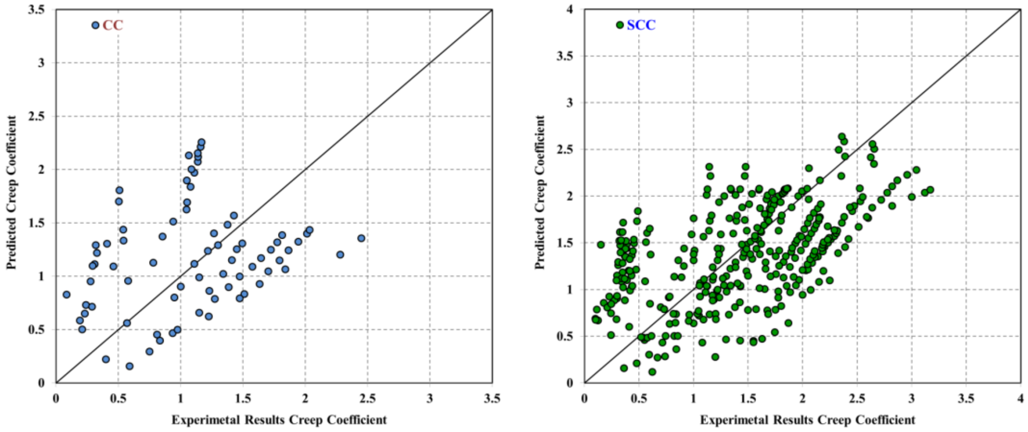

Fig. 7 Comparison of the CC and SCC creep coefficient from experimental results versus calculated values from AASHTO (2004) model

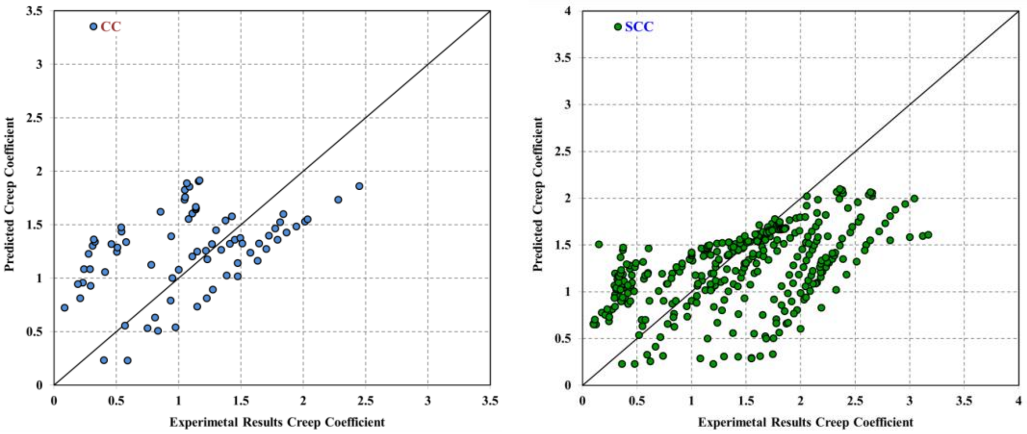

Fig. 8 Comparison of the CC and SCC creep coefficient from experimental results versus calculated values from AASHTO (2007) model

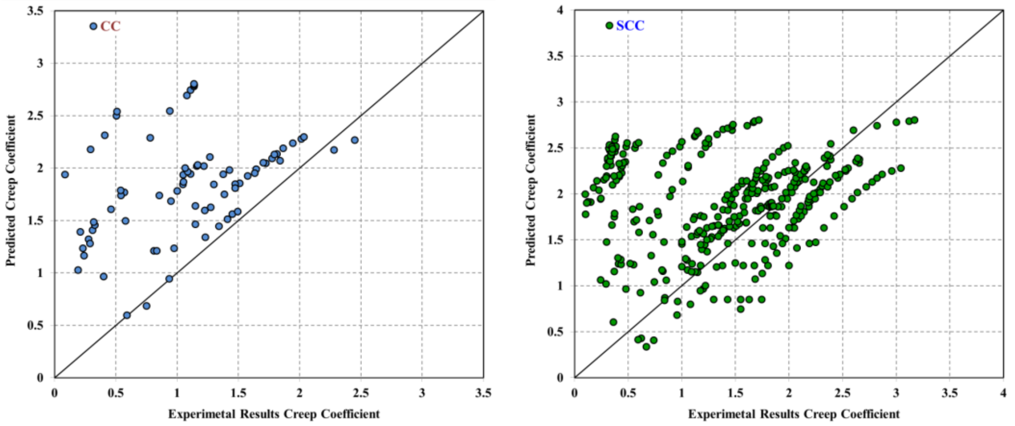

Fig. 9 Comparison of the CC and SCC creep coefficient from experimental results versus calculated values from AS 3600 (2009) model

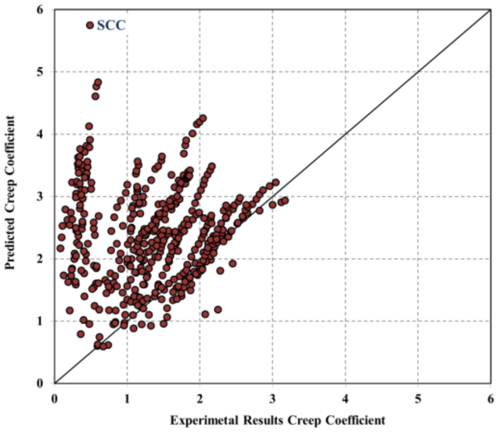

Fig. 10 Comparison of the SCC creep coefficient from experimental results versus calculated values from Poppe and De Schutter (2005) model

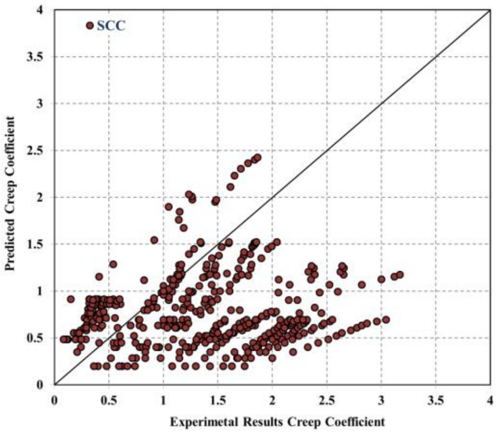

Fig. 11 Comparison of the SCC creep coefficient from experimental results versus calculated values from Larson (2006) model

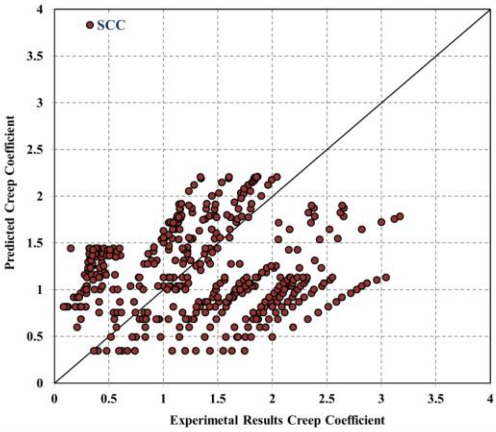

Fig. 12 Comparison of the SCC creep coefficient from experimental results versus calculated values from Cordoba (2007) model

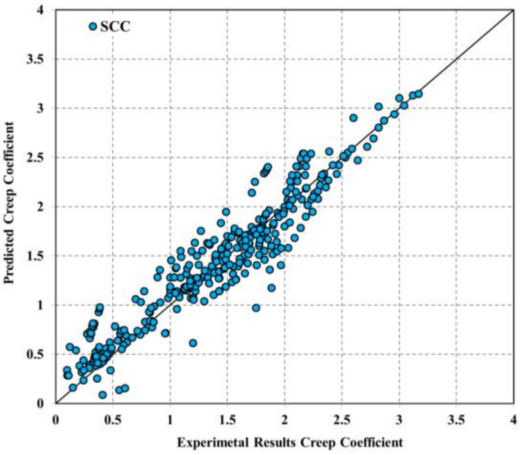

Fig. 13 Comparison of the SCC proposed creep model with experimental results database

Fig. 13 shows comparison of the proposed creep model with the available creep coefficient experimental results.

7. Evaluation of the models

7.1 CC creep models

As shown in Table 5 and Figs. 3 to 9 for the CC mixture included in the experimental database, the AASHTO (2007), JSCE (2002), Eurocode 2 (2001), AASHTO (2004) models provide better prediction of the creep strain with a coefficient of correlation factor (R^2) of 0.90, 0.89,0.89 and 0.86, respectively. Also, as shown in Table 5 and Figs. 3 to 9 for SCC mixture in the experimental database, AASHTO (2004), JSCE (2002), ACI 209R (1992) models provided better prediction of creep strain with a coefficient of correlation factor (R^2) of 0.87, 0.87 and 0.84, respectively.

As shown in AASHTO (2004), JSCE (2002), ACI 209R (1992), the CC models that have conservative predictions are different in the certain intrinsic and/or extrinsic variables. As indicated in the Table 3, the AASHTO (2004) model has not any intrinsic factors but the JSCE (2002) and ACI 209R (1992) models have a good consideration of both the intrinsic and the extrinsic variables. The modified composition of the SCC in comparison with the CC has an influence on the creep behaviour of the concrete. Therefore, it is important to include some key variables that have impact on this behaviour. By considerations of these variables, JSCE (2002) model can cover more reliable intrinsic and extrinsic variables for the SCC mixture.

7.2 SCC creep models

It can be seen from Table 6 and Fig.10 that Poppe and De Schutter (2005) model overestimates the creep coefficient of the SCC mixture. According to the Fig.11, Larson's (2006) creep prediction model underestimates the creep coefficient of the SCC mixture. According to Cordoba (2007) the SCC creep prediction model is more conservative underestimate for the creep strain of SCC experimental results (see Fig.12 and Table 6). In the Poppe and De Schutter (2005) investigation, ACI 209R (1997), CEB-FIP (1990), Le Roy *et al*. (1996) models are compared and it is found that CEB-FIP (1990) always leads to underestimation of the deformation. But, the CEB-FIP model's creep deformation prediction trend is suitable then it is selected as a basis model. The

Table 5 Coefficient of correlation factor (R^2) CC creep prediction models for CC and SCC

Creep prediction models	CC	SCC
	R^2	R^2
CEB-FIP (1990)	0.41	0.58
ACI 209R (1992)	0.79	0.84
Eurocode 2 (2001)	0.89	0.80
JSCE (2002)	0.89	0.87
AASHTO (2004)	0.86	0.87
AASHTO (2007)	0.90	0.80
AS 3600 (2009)	0.70	0.75

Table 6 Coefficient of correlation factor (R^2) CC creep prediction models for CC and SCC

Creep prediction models	SCC
	R^2
Poppe and De Schutter (2005)	0.57
Larson (2006)	0.72
Cordoba (2007)	0.81
Proposed model	0.93

modified model of CEB-FIP (1990) is just suitable for Poppe and De Schutter's experimental results.

The Larson's (2006) model is just a modification of ACI 209R (1997) model based on Larson's mixture. This model does not cover intrinsic and extrinsic variables. In the Cordoba's (2007) model, KL is first mixture that was based on a mixture developed by Khayat (1995) and modified by Altan (1999). This mixture achieves the SCC performance by replacing some of the coarse aggregates with cement. The second mixture, labelled KM, was based on the KL but with a coarse aggregate content increased to 38%. Similarly, the third mixture, KH, was based on the KL but has a coarse aggregate content of 39%. Cordoba's model is based on ACI 209R (1997) and it does not cover intrinsic and extrinsic variables.

7.3 SCC creep models

As shown in Table 6 and Fig. 13, the proposed model provides good predictions compared to the experimental database of the SCC mixtures. In the experimental database, normal and high strength SCC mixtures are available and the SCC proposed model has good prediction for both normal and high strength experimental results. Also, the c/p ratio that is included in the proposed model has effective influence on the overall creep prediction. As can be seen in Table 2 this ratio varies over a wide range.

8. Conclusions

In summary the following conclusions can be drawn from this study:

- The AASHTO (2004), JSCE (2002) and ACI 209R (1992) creep models provide a better prediction of the creep strain for SCC mixtures compared to the other models. However, these models are different in the certain intrinsic and/or extrinsic variables which JSCE (2002) model is better in this case.
- The AASHTO (2007), JSCE (2002), Eurocode 2 (2001) and AASHTO (2004) creep models provide a better prediction of the creep strain for CC mixtures too compared to the other models.
- The SCC creep model of Cordoba (2007) is more conservative compared with the other SCC models. This model is a modification of the ACI 209R (1997) model and it is based on the few mixture design available in the literature. Moreover, this model is a general view of ACI 209R (1997) because it does not cover intrinsic and extrinsic variables.
- Proposed model has good predictions for normal and high strength SCC mixtures as compared with the experimental database of SCC mixtures.

References

AASHTO (2004), Bridge design specifications and commentary, American Association of Highway and Transportation Officials (AASHTO), Washington, D.C.

AASHTO (2007), Interim bridge design specifications and commentary, American Association of Highway and Transportation Officials (AASHTO), Washington, D.C.

ACI 209 (1994), Prediction of creep, shrinkage, and temperature effects in concrete structures, ACI 209R-92, American Concrete Institute, Farmington Hills, Michigan.

ACI 209R (1997), Prediction of creep, shrinkage, and temperature effects in concrete structures, ACI 209R-92, American Concrete Institute, Farmington Hills, Michigan.

Altan, S. (1999), "Self-compacting concrete for precast/prestressed concrete applications", Thesis Louisiana State University.

AS 3600 (2009), Concrete structures, Standards Australia.

Aslani, F. (2014), "Experimental and numerical study of time-dependent behaviour of reinforced self-compacting concrete slabs", PhD Thesis, University of Technology, Sydney.

Aslani, F. and Nejadi, S. (2012a), "Mechanical properties of conventional and self-compacting concrete: An analytical study", *Constr. Build. Mater.*, **36**, 330-347.

Aslani, F. and Nejadi, S. (2012b), "Bond characteristics of steel fibre reinforced self-compacting concrete", *Can. J. Civil Eng.*, **39**(7), 834-848.

Aslani, F. and Nejadi, S. (2012c), "Bond behavior of reinforcement in conventional and self-compacting concrete," *Adv. Struct. Eng.*, **15**(12), 2033-2051.

Aslani, F. and Nejadi, S. (2012d), "Shrinkage behavior of self-compacting concrete," *J. Zhejiang Uni. Sci. A*, **13**(6), 407-419.

Aslani, F. and Nejadi, S. (2012e), "Bond characteristics of reinforcing steel bars embedded in self-compacting concrete", *Aust. J. Struct. Eng.*, **13**(3), 279-295.

Aslani, F. and Nejadi, S. (2013a), "Self-compacting concrete incorporating steel and polypropylene fibers: compressive and tensile strengths, moduli of elasticity and rupture, compressive stress-strain curve, and energy dissipated under compression", *Compos. Part B-Eng.*, **53**, 121-133.

Aslani, F. and Nejadi, S. (2013b), "Creep and shrinkage of self-compacting concrete with and without fibers", *J. Adv. Concr. Technol.*, **11**(10), 251-265.

Aslani, F. (2013), "Effects of specimen size and shape on compressive and tensile strengths of self-compacting concrete with or without fibers", *Mag. Concrete Res.*, **65**(15), 914-929.

Aslani, F. and Maia, L. (2013), "Creep and shrinkage of high strength self-compacting concrete experimental and numerical analysis", *Mag. Concrete Res.*, **65**(17), 1044-1058.

Aslani, F. and Natoori, M. (2013), "Stress-strain relationships for steel fibre reinforced self-compacting concrete", *Struct. Eng. Mech.*, **46**(2), 295-322.

Aslani, F. and Bastami, M. (2014), "Relationship between deflection and crack mouth opening displacement of self-compacting concrete beams with and without fibres", *Mech Adv Mater Struc*, doi: 10.1080/15376494.2014.906689.

Aslani, F., Nejadi, S. and Samali, B. (2014a), "Short term bond shear stress and cracking control of reinforced self-compacting concrete one way slabs under flexural loading", *Comput. Concrete*, **13**(6), 709-737.

Aslani, F., Nejadi, S. and Samali, B. (2014b), "Long-term flexural cracking control of reinforced self-compacting concrete one way slabs with and without fibres", *Comput. Concrete*, **14**(4), 419-443.

Aslani, F. and Samali, B. (2014), "Flexural toughness characteristics of self-compacting concrete incorporating steel and polypropylene fibers", *Aust. J. Struct. Eng.*, **15**(3), 269-286.

CEB-FIP (1990), *High-strength concrete state of the art report*, Thomas Telford, London.

Chopin, D., Francy, O., Lebourgeois, S. and Rougeau, P. (2003), "Creep and Shrinkage of Heat-cured Self-compacting Concrete (SCC)", *3rd International Symposium on Self-Compacting Concrete*, Reykjavik, Iceland.

Cordoba, B. (2007), "Creep and shrinkage of Self-Consolidating Concrete (SCC)", MSc Thesis, University of Wyoming.

Eurocode 2 (2001), European pre-standard ENV 1992-1-1: Design of concrete structures, Part 1: General rules and Rules for Buildings.

Heirman, G., Vandewalle, L., Van Gemerta, D., Boel, V., Audenaert, K., De Schutter, G., Desmetd, B. and Vantomme, J. (2008), "Time-dependent deformations of limestone powder type self-compacting concrete", *Eng. Struct.*, **3**, 2945-2956.

Horta, A. (2005), "Evaluation of Self-Consolidating Concrete for bridge structures applications", MSc Thesis, Georgia Institute of Technology.

Issa, M., Alhassan, M., Shabila, H. and Krozel, J. (2005), "Laboratory performance evaluation of self-consolidating concrete", *Proceeding of the Second North American Conference on the Des. and Use of Self Consolidating Concrete and the Fourth Int. RILEM Symposium on Self-Consolidating Concrete*, Center for Advanced Cement-Based Materials (ACBM), Chicago.

JSCE (2002), Standard specifications for concrete structure.

Khayat, K.H. (1995), "Effects of antiwashout admixtures on fresh concrete properties", *ACI Struct. J.*, **92**(2), 164-180.

Khayat, K.H. and Long, W.J. (2010), "Shrinkage of precast, prestressed Self-Consolidating Concrete", *ACI Mater. J.*, **107**(3), 231-238.

Kim, Y.H. (2008), "Characterization of Self-consolidating Concrete for the Design of Precast, Pretensioned Bridge Superstructure Elements", PhD Thesis, Texas A&M University.

Klug, Y. and Holschemaker, K. (2003), "Comparison of the hardened properties of self-compacting and normal vibrated concrete", *3rd RILEM Symposium on Self Compacting Concrete, Proc. Int. Conf.*, Reykjavik.

Landsberger, G.A. and Fernandez-Gomez J. (2007), "Evaluation of creep prediction models for self-consolidating concrete", *5th RILEM Symp. on SCC*, Pro 54, Ghent, **2**, 605-610.

Larson, K. (2006), "Evaluation the time-dependent deformation and bond characteristics of a self-consolidating concrete mix and the implication for pretensioned bridge applications", PhD Thesis, Kansas State University.

Le Roy, R., de Larrard, F. and Pons, G. (1996), "The AFREM code type model for creep and shrinkage of high performance concrete", *4th International Symposium on Utilization of High Strength/high Performance Concrete*, Eds. F. de Larrard and R. Lacroix, Paris.

Loser, R. and Leemann, A. (2009), "Shrinkage and restrained shrinkage cracking of self-compacting concrete compared to conventionally vibrated concrete", *Mater. Struct.*, **42**, 71-82.

Mazzotti, C., Savoia, M. and Ceccoli, C. (2006), "Creep and shrinkage of Self Compacting Concrete", *2nd fib Conference, Proc. Int. Conf.*, Naples.

Mazzotti, C. and Ceccoli, C. (2009), "Creep and shrinkage of self-compacting concrete: Experimental behavior and numerical model", *Creep, Shrinkage and Durability Mechanics of Concrete and Concrete Structures*, Eds. Tanabe *et al*., 667-673.

Naito, C.J., Parent, G. and Brunn, G. (2006), "Performance of bulb-tee girders made with self-consolidating concrete", *PCI J.*, **51**(6), 72-85.

Neville, A.M. (1996), *Properties of Concrete*, 4th Edition, John Wiley and Sons, Inc., New York, New York.

Oliva, M.G. and Cramer, S. (2008), "Self-consolidating concrete: creep and shrinkage characteristics", Report, University of Wisconsin.

Ouchi, M., Nakamura, S., Osterson, T., Hallberg, S. and Lwin, M. (2003), *Applications of Self-Compacting Concrete in Japan*, Europe and the United States, ISHPC.

Persson, B. (2001), "A comparison between mechanical properties of SCC and the corresponding properties of normal concrete", *Cement Concrete Res.*, **31**(2), 193-198.

Persson, B. (2005), "Creep of self-compacting concrete", *CONCREEP 7, Proc. Int. Conf.*, Nantes.

Poppe, A.M. and De Schutter, G. (2001), "Creep and shrinkage of self-compacting concrete", *Proceedings of the Sixth International Conference CONCREEP-6*, 563-568.

Poppe, A.M. and De Schutter, G. (2005), "Creep and shrinkage of Self-Compacting Concrete", *First International Symposium on Design, Performance and Use of Self-Consolidating Concrete SCC2005*, China.

Schindler, A.K., Barnes, R.W., Roberts, J.B. and Rodriguez, S. (2007), "Properties of self-consolidating concrete for prestressed members", *ACI Mater. J.*, **104**(1), 53-61.

Seng, V. and Shima, H. (2005), "Creep and shrinkage of self-compacting concrete with different limestone powder contents", *4th RILEM Symposium on self-compacting concrete, Proc. Int. Conf.*, Chicago.

Suksawang, N., Nassif, H.H. and Najim, H.S. (2006), "Evaluation of mechanical properties for self-consolidating, normal, and high-performance concrete", *Trans. Res. Record*, 36-45.

Turcry, P., Loukili, A., Haidar, K., Pijaudier-Cabot, G. and Belarbi, A. (2006), "Cracking tendency of Self-Compacting Concrete subjected to restrained shrinkage: experimental study and modelling", *J. Mater. Civil Eng.*, **18**(1), 46-54.

Vidal, T., Assié, S. and Pons, G. (2005), "Creep and shrinkage of self-compacting concrete and comparative study with model code", *CONCREEP 7, Proc. Int. Conf.*, Nantes, 541-546.

Zheng, J., Chao, P. and Luo, S. (2009), "Experimental study on factors influencing creep of Self-Compacting Concrete", *Second International Symposium on Design, Performance and Use of Self-Consolidating Concrete, SCC'2009*, China.

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