Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)
ISSN 1673-565X (Print); ISSN 1862-1775 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Shrinkage behavior of self-compacting concrete

Farhad ASLANI[†], Shami NEJADI
(*Centre for Built Infrastructure Research, School of Civil and Environmental Engineering, University of Technology Sydney, Australia*)
[†]E-mail: Farhad.Aslani@uts.edu.au

Received Dec. 13, 2011; Revision accepted Mar. 19, 2012; Crosschecked Apr. 16, 2012

Abstract: In the structures where long-term behavior should be monitored and controlled, creep and shrinkage effects have to be included precisely in the analysis and design procedures. Shrinkage varies with the constituent and mixture proportions, and depends on the curing conditions and the work environment as well. Self-compacting concrete (SCC) contains combinations of various components, such as aggregate, cement, superplasticizer, water-reducing agent and other ingredients which affect the properties of the SCC including shrinkage. Hence, the realistic prediction shrinkage strains of SCC are an important requirement of the design process for this type of concrete structures. This study reviews the accuracy of the conventional concrete (CC) shrinkage prediction models proposed by the international codes of practice, including CEB-FIP (1990), ACI 209R (1997), Eurocode 2 (2001), JSCE (2002), AASHTO (2004; 2007) and AS 3600 (2009). Also, SCC shrinkage prediction models proposed by Poppe and De Schutter (2005), Larson (2007), Cordoba (2007) and Khayat and Long (2010) are reviewed. Further, a new shrinkage prediction model based on the comprehensive analysis on both of the available models, i.e., the CC and the SCC is proposed. The predicted shrinkage strains are compared with the actual measured shrinkage strains in 165 mixtures of SCC and 21 mixtures of CC.

Key words: Self-compacting concrete (SCC), Conventional concrete (CC), Shrinkage, Long-term behavior, Concrete structures
doi:10.1631/jzus.A1100340 **Document code:** A **CLC number:** TU37

1 Introduction

Basically, the self-compacting concrete (SCC) 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 smaller maximum size of the coarse aggregate (Aslani and Nejadi, 2011a; 2012). These modifications in the composition of the mixture affect the behavior of the concrete in its hardened state, including the creep and the shrinkage deformations. The overall shrinkage of concrete corresponds to a combination of several shrinkages, that is, plastic shrinkage, autogenous shrinkage, drying shrinkage, thermal shrinkage, and carbonation (chemical) shrinkage. In designing the CC, shrinkage is taken as drying shrinkage, which is the strain associated with the loss of moisture from the concrete under drying conditions. The CC with a relatively high water cementitious material ratio (*w*/*c*) (higher than 0.40) exhibits a relatively low autogenous shrinkage, with values less than 100 μstrain (Davis, 1940). In contrast, the SCC used in precast, prestressed applications has typically a low *w*/*c* ratio (0.32 to 0.40). Lower *w*/*c* values, coupled with a high content of binder, lead to greater autogenous shrinkage. Such shrinkage increases with the use of finely ground supplementary cementitious materials and fillers employed in the SCC. Therefore, both drying and autogenous shrinkage deformations have to be accounted for in the structural detailing of the reinforced concrete and the prestressed concrete members (Khayat and Long, 2010).

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 claimed larger shrinkage of the SCC for precast, prestressed concrete, resulting in larger prestress losses (Issa *et al.*, 2005; Naito *et al.*, 2006; Suksawang *et al.*, 2006; Schindler *et al.*, 2007). Although mechanical properties of the SCC are superior to those of the CC, shrinkage of SCC is significantly high (Issa *et al.*, 2005). Naito *et al.* (2006) also found that the SCC exhibits higher shrinkage than the CC, which is due to the higher fine aggregate volume in the SCC, and that the shrinkage of the SCC and the CC was 40% and 6% higher than that of the ACI 209R (1997) prediction model, respectively.

Different methodologies are followed in different countries to obtain the SCC (Ouchi *et al.*, 2003), and few studies are available concerning its long-term behavior (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 Fernandez-Gomez, 2007). Moreover, it is not assessed if the long-term properties can be predicted with reference to the conventional mechanical and physical parameters only (such as strength, w/c), or the adoption of parameters concerning the mix design is needed.

The objectives of the present research are: (1) To establish an experimental results database of shrinkage. (2) To review the accuracies of the CC shrinkage prediction models proposed by international codes of practice, including CEB-FIP (1990), ACI 209R (1997), Eurocode 2 (2001), JSCE (2002), AASHTO (2004; 2007) and AS 3600 (2009). (3) To review the accuracies of the SCC shrinkage prediction models proposed by Poppe and De Schutter (2005), Larson (2007), Cordoba (2007) and Khayat and Long (2010). (4) To propose a new prediction shrinkage model based on the comprehensive analysis of the available models and the experimental results database of both the CC and the SCC.

2 Shrinkage experimental results database

The use of database with experimental results from previous studies is an important tool for studying the applicability of various shrinkage 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. 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 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 approximated.

Tables 1 and 2 present a general summary of the concrete mixtures included in the database. The database comprises test results from 14 different investigations, with a total of 165 different SCC mixtures and 21 CC mixtures for shrinkage tests. Table 1 includes complimentary information regarding the age of the concrete (in days) when shrinkage begins (ACWSB), final age of the concrete, relative humidity (RH), type of the specimen, type of the cement and type of the filler. Table 2 (p.410-411) includes information about the amount of the cement, filler and water, compressive strength (f'_c) and cement to powder (c/p) ratio for each mixtures that used in different investigations. Figs. 1 and 2 (p.412) show the CC and SCC experimental results database that is summarized in Table 1 (drying shrinkage vs. time). By considering experimental results of drying shrinkage in the database, the following conclusions are observed: (1) Increase in the water to binder ratio causes increase in the drying shrinkage. (2) The proper use of fly ash in the SCC can reduce drying shrinkage remarkably. (3) Increase in the volume of coarse aggregate can reduce drying shrinkage significantly. Additionally, the change in the sand volume ratio has little effect on the drying shrinkage of the medium strength SCC (Aslani and Nejadi, 2011b; 2011c).

Table 1 Shrinkage experimental database

Reference	SCC No.	CC No.	ACWSB (d)	Final age of concrete (d)	RH (%)	Type of specimen (mm)	Type of cement	Type of filler
Chopin *et al.* (2003)	5	1	1	365	50	Cylinder (90×280)	CEM I	Limestone
Poppe and De Schutter (2005)	4	0	1	1400	60	Prism (150×150×500)	CEM I 42.5 R, CEM I 52.5	Limestone
Horta (2005)	6	0	1	200	50	Cylinder (150×300)	CEM I, CEM III	Fly ash and GGBFS*
Larson (2006)	1	0	1	520	50	Prism (101.6×101.6×609.6), cylinder (114.3×609.6)	CEM III	Limestone
Turcry *et al.* (2006)	3	3	1	120, 150, 210	50	Prism (70×70×280)	CEM I 52.5, CEM II 42.5	Limestone
Cordoba (2007)	4	1	1	365	50	Cylinder (101.6×203.2, 101.6×1057.8)	CEM I/II	Fly ash and GGBFS
Heirman *et al.* (2008)	7	1	1	98	60	Cylinder (120×300)	CEM I 42.5 R, CEM III/A 42.5 N LA	Limestone
Bhattacharya (2008)	6	2	1	90	50	Prism (76.2×76.2×311.2)	CEM I	Limestone, silica fume and slag
Oliva and Cramer (2008)	11	4	1	350, 495	50	Prism (101.6×101.6×285.75)	CEM I	GGBFS
Hwang and Khayat (2009)	10	2	1	56	50	Prism (75×75285)	CSA type Gub-F/SF, Gub-S/SF and quaternary blended cement	Fly ash and limestone
Ma *et al.* (2009)	16	0	1	120, 150	60	Prism (100×100×515)	CEM I	Fly ash
Loser and Leemann (2009)	13	3	1	91	70	Prism (120×120×360)	CEM I 42.5 N, CEM II/A-LL 45.2 N	Fly ash and silica fume
Guneyisi *et al.* (2010)	63	2	1	50	50	Prism (70×70×280)	CEM I	Fly ash, GGBFS, silica fume and metakaolin
Khayat and Long (2010)	16	2	1	300	50	Cylinder (150×300)	MS and HE (similar to ASTM C150 Types I/II and III)	Fly ash
Total of 186 mixtures	165	21						

* GGBFS: ground granulated blast furnace slag

3 Conventional concrete shrinkage models

This study assesses the accuracies of seven commonly used international code type models to predict shrinkage strains without the need for shrinkage 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 inputs. The models considered are listed in Table 3 (p.412), which also shows the factors required by each model. In this study the accuracies of the shrinkage prediction models proposed by the international codes of practice, including CEB-FIP (1990), ACI 209R (1997), Eurocode 2 (2001), JSCE (2002), AASHTO (2004; 2007) and AS 3600 (2009) are compared with the actual measured shrinkage strains in 165 SCC mixtures and 21 CC mixtures. Figs. 3–9 (p.413-414) show comparisons of the shrinkage by available SCC and CC models with the experimental results available in the literature (Tables 1 and 2).

4 Self-compacting concrete shrinkage models

Table 4 (p.415) shows empirical models for calculating the shrinkage of the SCC, which vary in complexity and precision in the calculations. Figs. 10–13 show comparisons of the drying shrinkag by Poppe and De Schutter (2005), Larson (2007), Cordoba (2007) and Khayat and Long (2010) with the available shrinkage experimental results.

Table 2 Shrinkage experimental database in detail

Reference	Cement (kg/m^3)	Filler (kg/m^3)	c/p	w (kg/m^3)	f'^{*}_{c} (MPa)
Chopin *et al.* (2003)					
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	36.0
SCC5	347	177	0.66	139	39.1
CC	348	–	1.00	132	35.6
Poppe and De Schutter (2005)					
SCC1	300	300	0.50	165	59.0
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)					
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	87.0
7BL	461	97	0.83	181	77.7
67M	458	91	0.83	175	78.2
Larson (2006)					
SCC	446	–	1.00	224	51.7
CC	387	–	1.00	263	51.7
Turcry *et al.* (2006)					
SCC1	330	110	0.75	180	40.0
SCC2	350	139	0.72	198	42.0
SCC3	350	150	0.70	187	48.0
CC1	280	–	1.00	170	37.0
CC2	350	–	1.00	175	41.0
CC3	360	–	1.00	170	53.0
Heirman *et al.* (2008)					
SCC1	360	240	0.60	165	57.1
SCC3	360	240	0.60	165	69.2
SCC5	300	300	0.50	165	49.0
SCC14	360	240	0.60	144	68.4
SCC15	360	240	0.60	198	46.7
SCC16	360	240	0.60	165	73.3
SCC17	360	240	0.60	216	39.9
Loser and Leemann (2009)					
SCC2	310	–	1.00	179	71.1
CC2	512	–	1.00	155	51.2

Reference	Cement (kg/m^3)	Filler (kg/m^3)	c/p	w (kg/m^3)	f'_{c} (MPa)
Bhattacharya (2008)					
SCCA	386	112	0.78	154	61.9
SCCB	386	112	0.78	154	61.7
SCCC	386	112	0.78	154	58.0
SCCD	380	112	0.77	152	61.8
SCCE	386	112	0.78	161	67.4
SCCF	386	112	0.78	151	63.2
Hwang and Khayat (2009)					
35-C1-BC	474	475	0.50	166	53.2
35-C2-BC	474	475	0.50	166	49.5
35-C3-BC	474	475	0.50	166	46.1
42-N-B1	476	475	0.50	200	34.7
42-C2-B1	476	475	0.50	200	46.1
42-C3-B1	476	475	0.50	200	39.9
42-N-B2	476	475	0.50	200	42.2
42-C3-B2	476	475	0.50	200	46.0
42-C3-B3	476	475	0.50	200	37.1
SCC180	476	475	0.50	200	41.1
HPC180	357	428	0.45	150	51.6
CC	436	455	0.49	183	38.5
Ma *et al.* (2009)					
A1	386	166	0.70	166	44.1
A2	359	154	0.70	180	42.3
A3	335	144	0.70	192	33.6
B1	389	97	0.80	195	38.7
B2	335	144	0.70	192	35.2
B3	283	189	0.60	189	33.9
C1	394	131	0.75	210	30.4
C2	382	128	0.75	204	33.2
C3	370	125	0.75	198	35.9
C4	360	120	0.75	192	36.4
C5	348	117	0.75	186	39.1
C6	338	112	0.75	180	41.9
D1	390	130	0.75	208	51.7
D2	375	125	0.75	200	54.2
D3	360	120	0.75	192	53.3
D4	337	113	0.75	180	56.4
Cordoba (2007)					
KH	408	133	0.75	205	48.9
KM	418	136	0.75	210	48.2
CC	531	–	1.00	202	46.1

$^{*}f'_{c}$ for all tests is based on the 28-d compressive strength of 100 mm×200 mm cylinders, and it is based on the compressive strength of 150 mm cube except Heirman *et al.* (2008)

(To be continued)

(Table 2)

Reference	Cement (kg/m^3)	Filler (kg/m^3)	c/p	w (kg/m^3)	f'_c (MPa)	Reference	Cement (kg/m^3)	Filler (kg/m^3)	c/p	w (kg/m^3)	f'_c (MPa)
Guneyisi *et al.* (2010)						Guneyisi *et al.* (2010)					
M1	550	–	1	176	80.9	M51	427.5	22.5	0.95	144	60.7
M2	440	110	0.8	176	69.8	M52	405	45	0.9	144	58.5
M3	330	220	0.6	176	60.9	M53	382.5	67.5	0.85	144	71.1
M4	220	330	0.4	176	47.5	M54	360	90	0.8	144	61.5
M5	440	110	0.8	176	75.1	M55	270	180	0.6	144	46.9
M6	330	220	0.6	176	80.1	M56	180	270	0.4	144	37.4
M7	220	330	0.4	176	78.1	M57	360	90	0.8	144	60.1
M8	522.5	27.5	0.95	176	80.4	M58	270	180	0.6	144	58.3
M9	495	55	0.9	176	85.7	M59	180	270	0.4	144	57.6
M10	467.5	82.5	0.85	176	84.4	M60	360	90	0.8	144	62.4
M11	522.5	27.5	0.95	176	96.3	M61	270	180	0.6	144	53.6
M12	495	55	0.9	176	91.4	M62	180	270	0.4	144	45.9
M13	467.5	82.5	0.85	176	98.6	M63	360	90	0.8	144	60.6
M14	440	110	0.8	176	79.2	M64	270	180	0.6	144	54.7
M15	330	220	0.6	176	67.2	M65	180	270	0.4	144	44.2
M16	220	330	0.4	176	60.0	Khayat and Long (2010)					
M17	440	110	0.8	176	81.0	1	390	440	0.47	133	62.5
M18	330	220	0.6	176	84.2	2	530	440	0.55	180	62.5
M19	220	330	0.4	176	67.5	3	390	440	0.47	133	62.5
M20	440	110	0.8	176	79.6	4	530	440	0.55	180	62.5
M21	330	220	0.6	176	87.6	5	390	440	0.47	156	62.5
M22	220	330	0.4	176	84.5	6	530	440	0.55	212	62.5
M23	440	110	0.8	176	89.7	7	390	440	0.47	156	62.5
M24	330	220	0.6	176	81.2	8	530	440	0.55	212	62.5
M25	220	330	0.4	176	83.1	9	390	500	0.44	133	62.5
M26	440	110	0.8	176	77.0	10	530	500	0.51	180	62.5
M27	330	220	0.6	176	62.3	11	390	500	0.44	133	62.5
M28	220	330	0.4	176	69.4	12	530	500	0.51	180	62.5
M29	522.5	27.5	0.95	176	93.9	13	390	500	0.44	156	62.5
M30	495	55	0.9	176	92.6	14	530	500	0.51	212	62.5
M31	467.5	82.5	0.85	176	94.4	15	390	500	0.44	156	62.5
M32	440	110	0.8	176	78.5	16	530	500	0.51	212	62.5
M33	330	220	0.6	176	74.1	Kim (2008)					
M34	220	330	0.4	176	60.7	S5G-3	376	177	0.68	152	63.0
M35	440	110	0.8	176	90.6	S7G-4,5,6	427	107	0.80	123	79.0
M36	330	220	0.6	176	88.5	S5L-3	380	253	0.60	171	65.0
M37	220	330	0.4	176	74.1	S7L-4,5,6	427	107	0.80	133	88.0
M38	440	110	0.8	176	78.6	C5G	371	–	1.00	134	65.0
M39	330	220	0.6	176	72.7	C7G	415	–	1.00	119	73.0
M40	220	330	0.4	176	64.3	C5L	356	–	1.00	149	59.0
M41	440	110	0.8	176	91.2	C7L	403	–	1.00	133	72.0
M42	330	220	0.6	176	85.4	Zheng *et al.* (2009)					
M43	220	330	0.4	176	76.5	SCC1	440	110	0.80	180	52.6
M44	450	–	1.0	144	61.5	SCC2	250	300	0.45	154	46.5
M45	360	90	0.8	144	52.1	SCC3	288	192	0.60	145	47.7
M46	270	180	0.6	144	44.7	SCC4	312	208	0.60	156	51.0
M47	180	270	0.4	144	30.3	SCC5	330	220	0.60	165	52.0
M48	360	90	0.8	144	59.0	SCC6	330	220	0.60	155	43.8
M49	270	180	0.6	144	58.0	SCC7	330	220	0.60	165	40.5
M50	180	270	0.4	144	56.2	CC	525	0	1.00	200	41.3

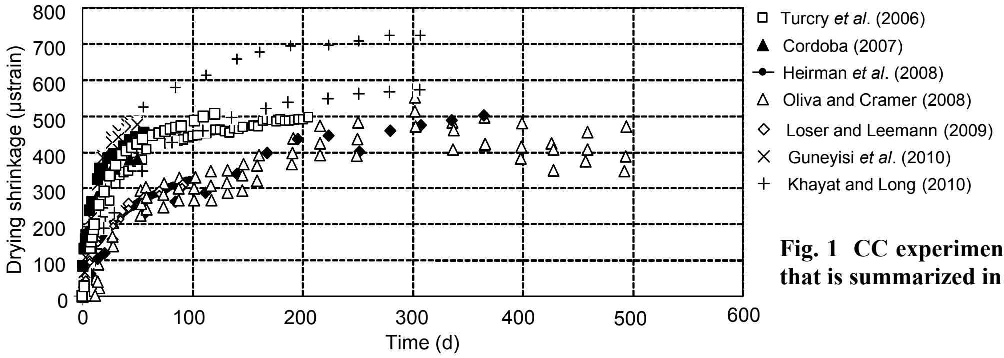

Fig. 1 CC experimental results database that is summarized in Table 1

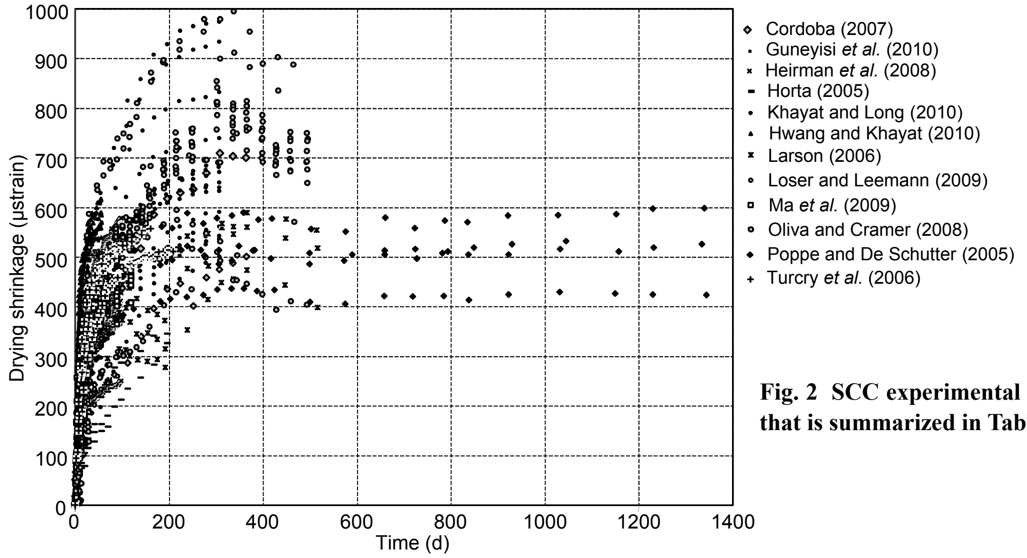

Fig. 2 SCC experimental results database that is summarized in Table 1

Table 3 Summary of factors accounted for by different prediction models

Factor	CEB-FIP (1990)	ACI 209R (1997)	Eurocode 2 (2001)	JSCE (2002)	AASHTO (2004)	AASHTO (2007)	AS 3600 (2009)
Intrinsic factor							
Aggregate type							
Aggregates/Cement ratio							
Air content		√					√
Cement content	√		√	√			
Cement type							
Concrete density		√					√
Fine/Total aggregate ratio (in mass)		√					√
Slump		√					√
w/*c* ratio				√			
Water content				√			
Extrinsic factor							
Age at the first loading	√	√	√	√	√	√	√
Age of sample				√			
Applied stress	√	√	√	√			√
Characteristic strength at loading							
Cross-section shape				√			
Curing conditions							
Compressive strength at 28 d	√	√	√	√	√	√	√
Duration of load	√	√	√	√			√
Effective thickness	√	√	√	√	√	√	√
Elastic modulus at age of loading							
Elastic modulus at 28 d	√	√	√	√			√
Relative humidity	√	√	√	√	√	√	√
Temperature				√			
Time drying commences							

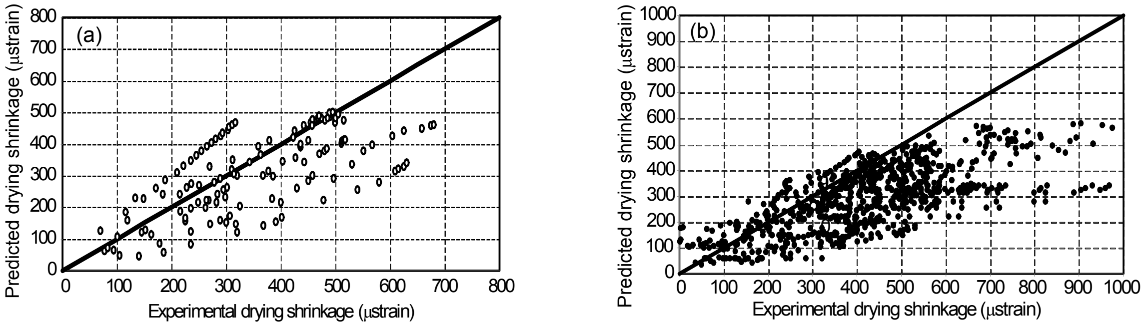

Fig. 3 Comparison of the CC (a) and SCC (b) drying shrinkage from experimental results vs. calculated values in CEB-FIP (1990) model

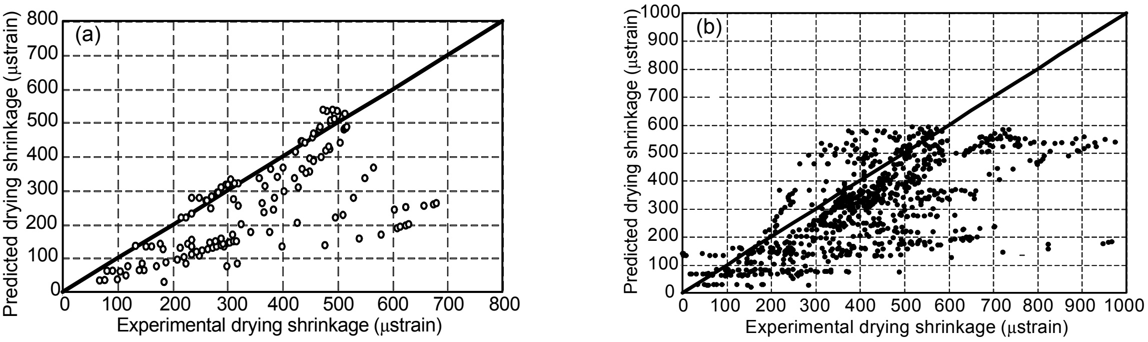

Fig. 4 Comparison of the CC (a) and SCC (b) drying shrinkage from experimental results vs. calculated values in ACI 209R (1997) model

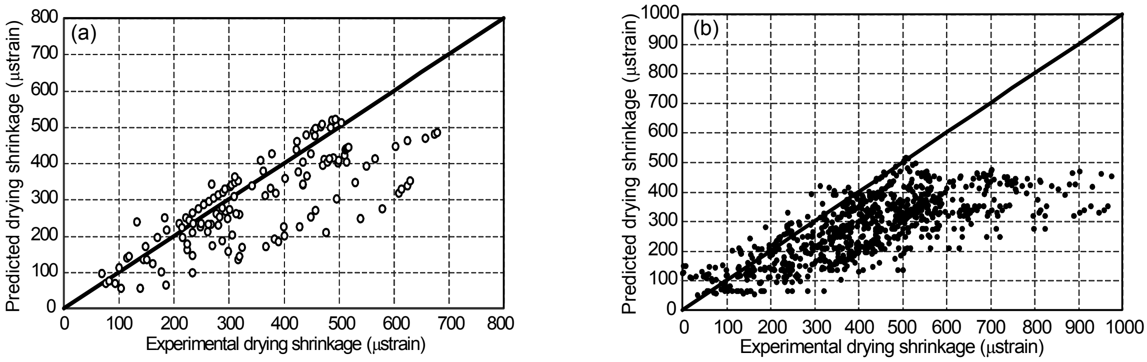

Fig. 5 Comparison of the CC (a) and SCC (b) drying shrinkage from experimental results vs. calculated values in Eurocode 2 (2001) model

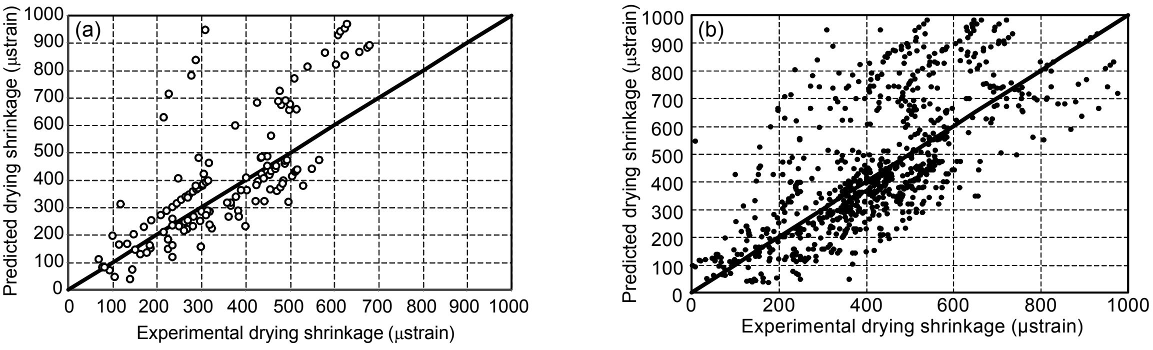

Fig. 6 Comparison of the CC (a) and SCC (b) drying shrinkage from experimental results vs. calculated values in JSCE (2002) model

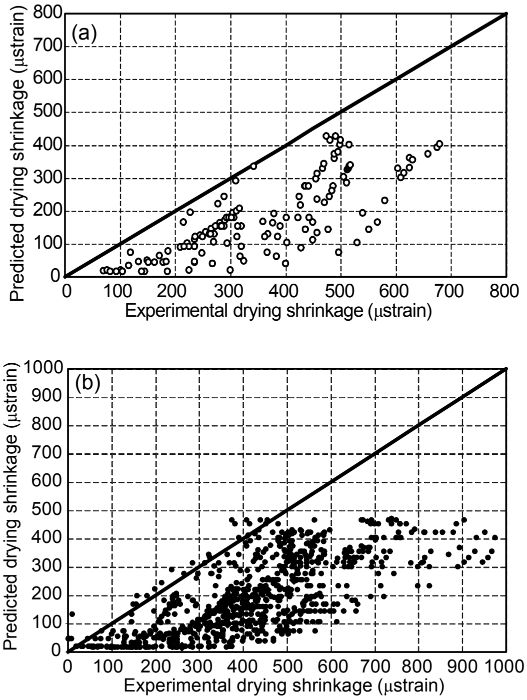

Fig. 7 Comparison of the CC (a) and SCC (b) drying shrinkage from experimental results vs. calculated values in AASHTO (2004) model

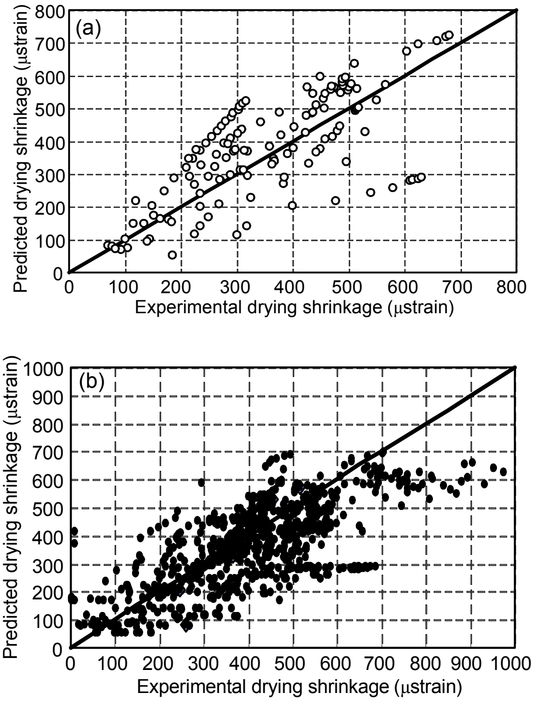

Fig. 8 Comparison of the CC (a) and SCC (b) drying shrinkage from experimental results vs. calculated values in AASHTO (2007) model

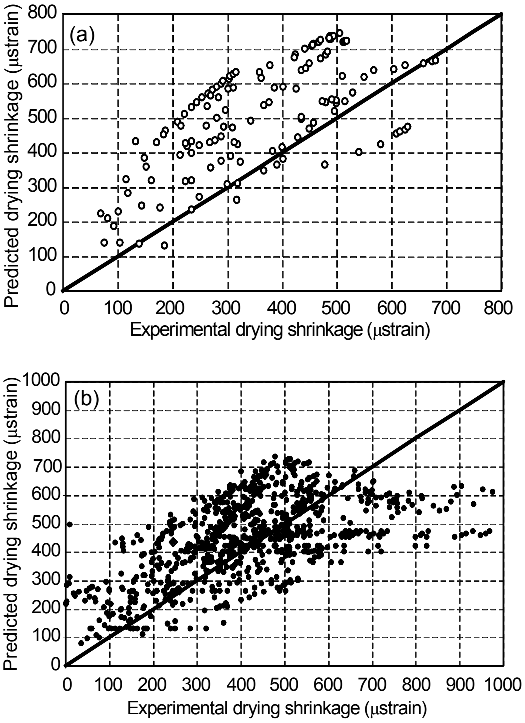

Fig. 9 Comparison of the CC (a) and SCC (b) drying shrinkage from experimental results vs. calculated values in AS 3600 (2009) model

5 Proposed self-compacting concrete shrinkage model

The comparisons of different models and experimental database show that ACI 209R (1997), JSCE (2002) and AASHTO (2004) models have conservative drying shrinkage predictions. In this study, required certain intrinsic and/or extrinsic variables (i.e., mix proportions, material properties and age of loading) for the SCC are shown in Table 3. Table 3 shows that JSCE (2002) drying shrinkage model gives good coverage of the intrinsic and/or extrinsic variables that are useful for calculating the drying shrinkage strain. Therefore, with the JSCE (2002) model as a basis, it is tried in the current study to include the *c*/*p* ratio into the formulas in order to obtain a better prediction of the time-dependent deformations of the normal strength and the high strength of the SCC. These results are shown in Eqs. (1)–(8).

For normal strength SCC with the range of applicability, $45\%\leq RH\leq 80\%$, $130\ \mathrm{kg/m^3}\leq w\leq 230\ \mathrm{kg/m^3}$, $100\ \mathrm{mm}\leq v/s\leq 300\ \mathrm{mm}$, $40\%\leq w/c\leq 65\%$, $f_c'(28)\leq$

Table 4 SCC shrinkage models

<table>
<tr><th>Reference</th><th>Modified shrinkage prediction model</th><th>Main model</th></tr>
<tr><td>Poppe and De Schutter (2005)</td><td>$\varepsilon_{\mathrm{sh}}(t,t_{\mathrm{s}})=\left[\frac{160}{1-\alpha(w/c)}+10\beta_{\mathrm{sc}}\left(9-\frac{f_{\mathrm{cm}}}{f_{\mathrm{cm0}}}\right)\right]\times\left\{-1.55\left[1-\left(\frac{\mathrm{RH}}{\mathrm{RH}_0}\right)^3\right]\right\}$
$\times\left[\frac{(t-t_{\mathrm{s}})/t_1}{45.5(h/h_0)^2+(t-t_{\mathrm{s}})/t_1}\right]^{\gamma}$</td><td>CEB-FIP (1990)</td></tr>
<tr><td>Larson (2006)</td><td>For square specimens: $(\varepsilon_{\mathrm{sh}})_t=\frac{t}{20+t}\times 550\times 10^{-6}$,
For cylindrical specimens: $(\varepsilon_{\mathrm{sh}})_t=\frac{t}{20+t}\times 600\times 10^{-6}$</td><td>ACI 209R (1997)</td></tr>
<tr><td>Cordoba (2007)</td><td>$(\varepsilon_{\mathrm{sh}})_t=\frac{t^{\alpha}}{f+t^{\alpha}}(\varepsilon_{\mathrm{sh}})_{\mathrm{u}}$
<table>
<tr><th rowspan="2">Mixtures</th><th colspan="3">2-year shrinkage fit coefficient</th></tr>
<tr><th>α</th><th>f(d)</th><th>$(\varepsilon_{\mathrm{sh}})_{\mathrm{u}}$</th></tr>
<tr><td>KM</td><td>0.75</td><td>56.9</td><td>847.1</td></tr>
<tr><td>KH</td><td>0.66</td><td>23.3</td><td>1033.8</td></tr>
<tr><td>Regular</td><td>0.71</td><td>29.7</td><td>990.0</td></tr>
<tr><td>Normal value</td><td>0.94−1.10</td><td>20−130</td><td>$415\mu\varepsilon-1070\mu\varepsilon$</td></tr>
</table></td><td>ACI 209R (1997)</td></tr>
<tr><td>Khayat and Long (2010)</td><td>$\varepsilon_{\mathrm{sh}}=-k_{\mathrm{s}}k_{\mathrm{h}}\left(\frac{t}{55+t}\right)(0.56\times 10^3)\times A(\text{steam-cured})$,
$k_{\mathrm{s}}=\left[\frac{\frac{t}{26\mathrm{e}^{0.0142(v/s)}+t}}{\frac{t}{45+t}}\right]\left[\frac{1064-3.70(v/s)}{923}\right]$,
where A is the cement factor, 0.918 for Type MS cement and 1.065 for Type HE+20% fly ash</td><td>AASHTO (2004)</td></tr>
</table>

[*] $\varepsilon_{\mathrm{sh}}$ is the shrinkage strain, β_{sc} is a coefficient that depends on the type of cement ($\beta_{\mathrm{sc}}=4$ for slowly hardening cements, 5 for normal or rapid hardening cements, and 8 for rapid hardening high strength cements), f_{cm} is the mean compressive strength of concrete at the age of 28 d (MPa), $f_{\mathrm{cmo}}=10$ MPa, RH is the relative humidity of the ambient environment in percent, $\mathrm{RH}_0=100\%$, h is the notional size of member (mm), $h_0=100$ mm, and $t_1=1$ d, $\gamma=-2.5(c/p)+2.6$, and α is the empirical constant, $\alpha=4.1(c/p)-1.8$; v/s is the volume to surface ratio, $(\varepsilon_{\mathrm{sh}})_{\mathrm{u}}$ is the ultimate shrinkage strain, and f is the constant based on the duration of curing

55 MPa, 260 kg/m$^3\le c\le$500 kg/m^3,

$$\varepsilon'_{\mathrm{cs}}(t,t_0)=\varepsilon'_{\mathrm{sh}}\{1-\exp[-0.1(t-t_0)^{(-2.4(c/p)+2.3)}]\}. \tag{1}$$

For $c/p<0.65$,

$$\varepsilon'_{\mathrm{sh}}=\left\{-50+78\left[1-\exp\left(\frac{\mathrm{RH}}{100}\right)\right]+38.3\ln w -0.92\ln\left(\frac{w}{c}\right)-5\left[\ln\left(\frac{v/s}{10}\right)\right]^2\right\}\times 10^{-5}; \tag{2}$$

For $c/p\ge 0.65$,

$$\varepsilon'_{\mathrm{sh}}=\left\{-50+78\left[1-\exp\left(\frac{\mathrm{RH}}{100}\right)\right]+37.5\ln w -0.92\ln\left(\frac{w}{c}\right)-5\left[\ln\left(\frac{v/s}{10}\right)\right]^2\right\}\times 10^{-5}, \tag{3}$$

where $\varepsilon'_{\mathrm{cs}}(t, t_0)$ is the shrinkage strain of concrete from the age of t_0 to t, $\varepsilon'_{\mathrm{sh}}$ is the final value of shrinkage strain, t is the temperature adjusted concrete age, and t_0 is the starting drying concrete age.

For high strength SCC with the range of applicability, 45%≤RH≤90%, 130 kg/m$^3\le w\le$230 kg/m^3, 100 mm≤v/s≤300 mm, 40%≤w/c≤65%, $f_c'(28)\le$ 80 MPa,

$$\varepsilon'_{\mathrm{cs}}(t,t_0)=\varepsilon'_{\mathrm{ds}}(t,t_0)+\varepsilon'_{\mathrm{as}}(t,t_0), \tag{4}$$

$$\varepsilon'_{\mathrm{ds}}(t,t_0)=\frac{\varepsilon'_{\mathrm{ds}\infty}(t-t_0)}{\beta+(t-t_0)}, \tag{5}$$

$$\varepsilon'_{\mathrm{ds}\infty}=\frac{\varepsilon'_{\mathrm{ds}\rho}}{\eta t_0}\times 10^{-6}, \tag{6}$$

where

$$\varepsilon'_{\rm as}(t,t_0)=\varepsilon'_{\rm as}(t)-\varepsilon'_{\rm as}(t_0),$$
$$\varepsilon'_{\rm as}(t)=\gamma\varepsilon'_{{\rm as}\infty}\{1-\exp[-a(t-t_{\rm s})^b]\}\times10^{-6},$$
$$\varepsilon'_{{\rm as}\infty}=3070\exp[-7.2(w/c)],$$

where $\varepsilon'_{\rm ds}(t, t_0)$ is the drying shrinkage strain of concrete from age t_0 to t, $\varepsilon'_{\rm as}(t, t_0)$ is the autogenous shrinkage strain of concrete from age t_0 to t, $\varepsilon'_{{\rm ds}\infty}$ is the final value of drying shrinkage strain, and β represents time dependency of drying shrinkage, $\beta=\dfrac{4w\sqrt{v/s}}{100+0.7t_0}$. The variations of a and b constants with w/c ratio are given in Table 5.

Table 5 Variations of *a* and *b* constants with *w*/*c* ratio

w/c	a	b
0.20	1.2	0.4
0.23	1.5	0.4
0.30	0.6	0.5
0.40	0.1	0.7
≥0.50	0.03	0.8

For $c/p<0.65$,

$$\varepsilon'_{{\rm ds}\rho}=\left\{\frac{\alpha(1-{\rm RH}/100)w}{1+110\exp[-400/f'_{\rm c}(28)]}\right\}\times[0.015+1.35(c/p)]^{-1}; \tag{7}$$

For $c/p\geq0.65$,

$$\varepsilon'_{{\rm ds}\rho}=\left\{\frac{\alpha(1-RH/100)w}{1+110\exp[-410/f'_{\rm c}(28)]}\right\}\times[0.015+1.05(c/p)]^{-1}, \tag{8}$$

where $\varepsilon'_{{\rm ds}\rho}$ is the final value of drying shrinkage strain, $\varepsilon'_{{\rm as}\infty}$ is the final value of autogenous shrinkage strain, α is the coefficient representing the influence of the cement type, α=11 for normal and low heat cement, and α=15 for high early strength cement.

The effective age (days) of concrete during loading can be written as

$$t=\sum_{i=1}^{n}\Delta t_i\exp\left[13.65-\frac{4000}{273+T(\Delta t_i)/T_0}\right], \tag{9}$$

where Δt_i is the number of days where the temperature T prevails. $T(\Delta t_i)$ is the temperature (°C) during the time period Δt_i, T_0=1 °C and γ is the coefficient representing the influence of the cement and admixtures type (maybe 1 when only ordinary Portland cement is used).

Fig. 14 shows comparison of the proposed drying shrinkage model with the available drying shrinkage experimental results.

6 Results and discussion

6.1 CC shrinkage models

As shown in the Table 6 and Figs. 3–9 for the CC mixture in the experimental database, the AASHTO (2007) and JSCE (2002) models provided a better prediction of the drying shrinkage data with coefficient of correlation factors (R^2) of 0.88 and 0.84 compared to the other models, respectively. Also for the SCC mixture in the experimental database, the AASHTO (2007), JSCE (2002) and AS 3600 (2009) models provided a better prediction of drying shrinkage data with R^2 of 0.86, 0.83 and 0.80 compared to the other models, respectively.

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

Shrinkage prediction model	R^2	
	CC	SCC
CEB-FIP (1990)	0.70	0.57
ACI 209R (1997)	0.62	0.66
Eurocode 2 (2001)	0.72	0.55
JSCE (2002)	0.84	0.83
AASHTO (2004)	0.42	0.47
AASHTO (2007)	0.88	0.86
AS 3600 (2009)	0.65	0.80

As shown in AASHTO (2007) and JSCE (2002), the CC models that have conservative predictions for the SCC mixtures in the database are different in the certain intrinsic and/or extrinsic variables. As mentioned in Table 3, the AASHTO (2007) model has not any intrinsic factors but the JSCE (2002) model has a good consideration of both the intrinsic and the extrinsic variables. The modified composition of the SCC in comparison with the CC has influence on the shrinkage behavior of the concrete. Therefore, it is important to include some variables that have impact on this behavior. By considering these variables, JSCE (2002) model can cover more and reliable intrinsic and extrinsic variables for the SCC mixture.

6.2 SCC shrinkage models

It can be seen from Figs. 10 and 13 that Poppe and De Schutter (2005) and Khayat and Long (2010)'s models overestimate the drying shrinkage of the SCC mixture. According to Larson (2007) and Cordoba (2007), the SCC drying shrinkage prediction models are more conservative underestimated for the shrinkage strain of SCC experimental results (Figs. 11 and 12).

In (Poppe and De Schutter, 2005), ACI 209R (1997), CEB-FIP (1990) and Le Roy *et al.* (1996)'s models are compared and it is found that CEB-FIP (1990) always leads to underestimation of the deformation. When the CEB-FIP (1990) shape of the shrinkage deformation is suitable, then this model is selected as a basis model. But the modified model of CEB-FIP (1990) is just suitable for Poppe and De Schutter (2005)'s experimental results.

About the Larson (2006)'s model, it is just a modification of ACI 209R (1997) model based on their mixture in the SCC mixture database. This model does not cover intrinsic and extrinsic variables.

In the Cordoba (2007)'s model, KL is the 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, labeled 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 (2007)'s model is a general view of ACI 209R (1997) because it does not protect intrinsic and extrinsic variables.

Khayat and Long (2010)'s shrinkage model is a modification of the AASHTO (2004) model. They defined a factor that is related to the cement type used

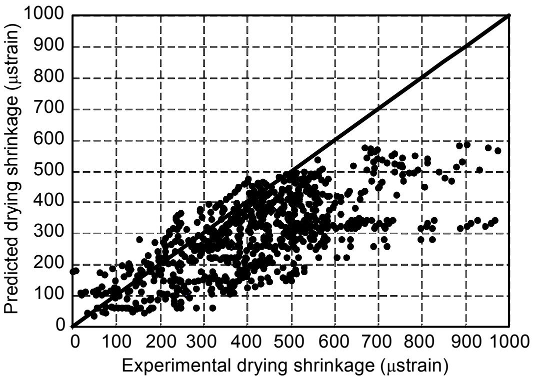

Fig. 10 Comparison of the SCC drying shrinkage from experimental results vs. calculated values from Poppe and De Schutter (2005)'s model

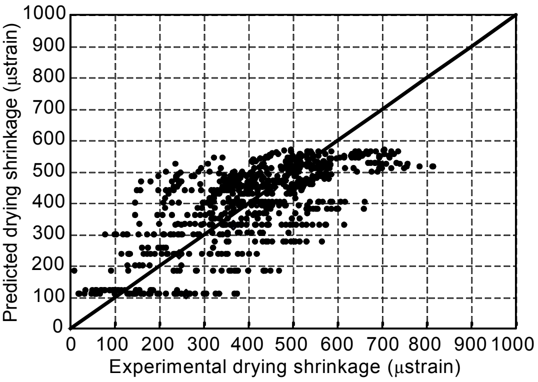

Fig. 11 Comparison of the SCC drying shrinkage from experimental results vs. calculated values from Larson (2006)'s model

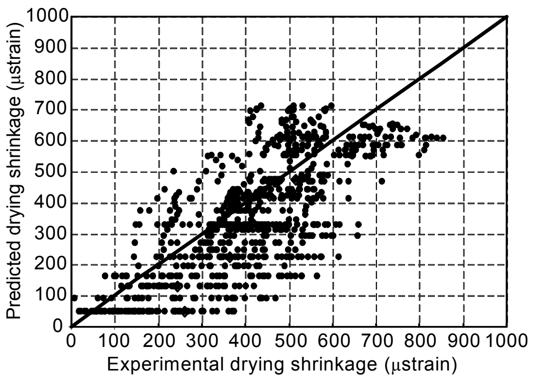

Fig. 12 Comparison of the SCC drying shrinkage from experimental results vs. calculated values from Cordoba (2007)'s model

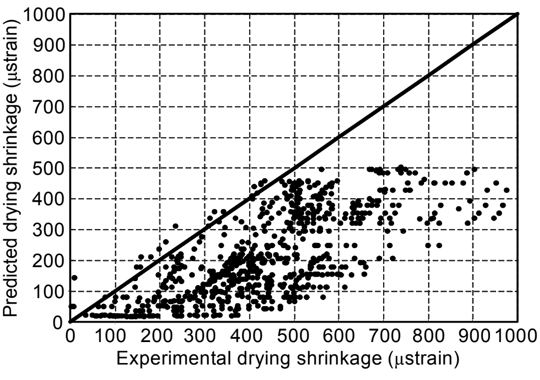

Fig. 13 Comparison of the SCC drying shrinkage from experimental results vs. calculated values from Khayat and Long (2010)'s model

in the mixture design. As mentioned in Table 3, the AASHTO (2004) model does not have any intrinsic factors. Therefore, this model is modified by considering cement type.

6.3 Proposed SCC shrinkage model

As shown in Fig. 14, the proposed model has good predictions compared to the experimental database of SCC mixtures. In the experimental database, normal strength and high strength of the SCC mixtures are available. The SCC proposed model has good prediction for both normal strength and high strength experimental results. Also, the *c*/*p* ratio included in the proposed model has an effective influence on the overall shrinkage prediction. The experimental results of *c*/*p* ratios as shown in Table 2 are very variable but the proposed model can predict well the drying shrinkage strain.

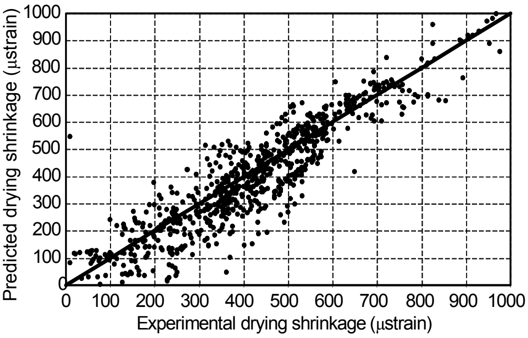

Fig.14 Comparison of proposed shrinkage SCC model with experimental results database

7 Conclusions

In summary, the following conclusions can be drawn:

1. For the SCC mixtures, the AASHTO (2007), JSCE (2002) and AS 3600 (2009) CC models provided better prediction of the shrinkage data compared to the other models. But these models are different in the certain intrinsic and/or extrinsic variables, and JSCE (2002) model is better in this case.

2. For the CC mixtures, the AASHTO (2007) and JSCE (2002) models provided better prediction of the shrinkage data compared to the other models.

3. Larson (2007) and Cordoba (2007)'s SCC shrinkage prediction model is more conservative as it is likely to underestimate the SCC experimental results. These models are a modification of the ACI 209R (1997) model. Also, these models are a general view of ACI 209R (1997) because they do not cover intrinsic and extrinsic variables.

4. The proposed model has good prediction for normal strength and high strength of the SCC mixtures compared to the experimental database of the SCC mixtures.

References

AASHTO, 2007. AASHTO LRFD Bridge Design Specifications, 3rd Edition. American Association of Highway and Transportation Officials, Washington DC.

AASHTO, 2007. Bridge Design Specifications and Commentary. American Association of Highway and Transportation Officials, Washington DC.

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. MS Thesis, Louisiana State University, USA.

AS 3600, 2009. Concrete Structures. Standards Australia.

Aslani, F., Nejadi, S., 2011a. Comparison of the Analytical Models to Determine Modulus of Elasticity of Self-Compacting Concrete and Conventional Concrete. Structural Engineers World Congress (SEWC), Technical Committee, Italy, p.1-10.

Aslani, F., Nejadi, S., 2011b. Comparison of Shrinkage Prediction Models for Self-Compacting and Conventional Concrete. 9th International Symposium on High Performance Concrete, Khrapko, M., Wallevik, O. (Eds.), New Zealand Concrete Society, New Zealand, p.1-10.

Aslani, F., Nejadi, S., 2011c. Evaluation and Comparison of the Analytical Models to Predict Creep and Shrinkage Behavior of Self-Compacting Concrete. Structural Engineers World Congress (SEWC), Technical Committee, Italy, p.1-10.

Aslani, F., Nejadi, S., 2012. Mechanical properties of conventional and self-compacting concrete: an analytical study. *Construction and Building Materials*, in press. [doi:10.1016/j.conbuildmat.2012.04.034]

CEB-FIP, 1990. High-Strength Concrete State of the Art Report. Thomas Telford, London.

Chopin, D., Francy, O., Lebourgeois, S., Rougeau, P., 2003. Creep and Shrinkage of Heat-Cured Self-Compacting Concrete (SCC). 3rd International Symposium on Self-Compacting Concrete, Reykjavik, Iceland, p.672-683.

Cordoba, B., 2007. Creep and Shrinkage of Self-Consolidating Concrete (SCC). MS Thesis, University of Wyoming, Australia.

Davis, H.E., 1940. Autogenous Volume Change of Concrete. Proceedings, 43rd Annual American Society for Testing Materials Meeting, Atlantic City, NJ, p.1103-1113.

Eurocode 2, 2001. European Pre-Standard ENV 1992-1-1: Design of Concrete Structures. Part 1: General Rules and Rules for Buildings.

Guneyisi, E., Gesoglu, M., Ozbay, E., 2010. Strength and drying shrinkage properties of self-compacting concretes incorporating multi-system blended mineral admixtures. *Construction and Building Materials*, **24**(10):1878-1887.

Heirman, G., Vandewalle, L., Van Gemerta, D., Boel, V., Audenaert, K., De Schutter, G., Desmetd, B., Vantomme, J., 2008. Time-dependent deformations of limestone powder type self-compacting concrete. *Engineering Structures*, **3**:2945-2956. [doi:10.1016/j.engstruct.2008.04.009]

Horta, A., 2005. Evaluation of Self-Consolidating Concrete for Bridge Structures Applications. MS Thesis, Georgia Institute of Technology.

Hwang, S.D., Khayat, K., 2010. Effect of mix design on restrained shrinkage of self-consolidating concrete. *Materials and Structures*, **43**:367-380. [doi:10.1617/s11527-009-9495-x]

Issa, M., Alhassan, M., Shabila, H., Krozel, J., 2005. Laboratory Performance Evaluation of Self-Consolidating Concrete. Proceedings of the Second North American Conference on the Design and Use of Self-Consolidating Concrete and the Fourth Int. RILEM Symposium on Self-Consolidating Concrete, Center for Advanced Cement-Based Materials (ACBM), Chicago, p.857-862.

JSCE, 2002. Standard Specifications for Concrete Structure.

Khayat, K.H., 1995. Effects of antiwashout admixtures on fresh concrete properties. *ACI Structural Journal*, **92**(2): 164-180.

Khayat, K.H., Long, W.J., 2010. Shrinkage of precast, prestressed self-consolidating concrete. *ACI Materials Journal*, **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., Holschemaker, K., 2003. Comparison of the Hardened Properties of Self-Compacting and Normal Vibrated Concrete. 3rd RILEM Symposium on Self Compacting Concrete, Reykjavik, p.596-605.

Landsberger, G.A., Fernandez-Gomez, J., 2007. Evaluation of Creep Prediction Models for Self-Consolidating Concrete. 5th RILEM Symposium on Self Compacting Concrete, Ghent, **2**:605-610.

Larson, K., 2006. Evaluating 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, USA.

Le Roy, R., De Larrard, F., 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, De Larrard, F., Lacroix, R. (Eds.), Paris, p.387-396.

Loser, R., Leemann, A., 2009. Shrinkage and restrained shrinkage cracking of self-compacting concrete compared to conventionally vibrated concrete. *Materials and Structures*, **42**:71-82. [doi:10.1617/s11527-008-9367-9]

Ma, K., Xie, Y., Long, G., Luo, Y., 2009. Drying Shrinkage of Medium Strength SCC. Second International Symposium on Design, Performance and Use of Self-Consolidating Concrete, China, p.657-663.

Mazzotti, C., Savoia, M., Ceccoli, C., 2006. Creep and Shrinkage of Self Compacting Concrete. 2nd FIB Conference, Proc. Int. Conf., Naples, p.1-10.

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

Oliva, M.G., Cramer, S., 2008. Self-Consolidating Concrete: Creep and Shrinkage Characteristics. Report, University of Wisconsin.

Ouchi, M., Nakamura, S., Osterson, T., Hallberg, S., Lwin, M., 2003. Applications of Self-Compacting Concrete in Japan, Europe and the United States. International Symposium on High Performance Computing (ISHPC), p.1-20.

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

Persson, B., 2005. Creep of Self-Compacting Concrete. Proceedings of the Seventh International Conference, Nantes, p.535-540.

Poppe, A.M., De Schutter, G., 2001. Creep and Shrinkage of Self-Compacting Concrete. Proceedings of the Sixth International Conference, p.563-568.

Poppe, A.M., De Schutter, G., 2005. Creep and Shrinkage of Self-Compacting Concrete. First International Symposium on Design, Performance and Use of Self-Consolidating Concrete, China, p.329-336.

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

Seng, V., Shima, H., 2005. Creep and Shrinkage of Self-Compacting Concrete with Different Limestone Powder Contents. 4th RILEM Symposium on Self-Compacting Concrete, Chicago, p.981-987.

Suksawang, N., Nassif, H.H., Najim, H.S., 2006. Evaluation of Mechanical Properties for Self-Consolidating, Normal, and High-Performance Concrete. *Transportation Research Record of the National Academics*, **1979**:36-45. [doi:10.3141/1979-07]

Turcry, P., Loukili, A., Haidar, K., Pijaudier-Cabot, G., Belarbi, A., 2006. Cracking tendency of self-compacting concrete subjected to restrained shrinkage: experimental study and modelling. *Journal of Materials in Civil Engineering*, **18**(1): 46-54. [doi:10.1061/(ASCE)0899-1561(2006)18:1(46)]

Vidal, T., Assié, S., Pons, G., 2005. Creep and Shrinkage of Self-Compacting Concrete and Comparative Study with Model Code. Proceedings of the Seventh International Conference, Ecole Centrale de Nantes, France, p.541-546.

Zheng, J., Chao, P., 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, China, p.703-709.