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Creep and shrinkage of high-strength self-compacting concrete: experimental and analytical analysis

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In the present paper, a numerical and experimental study about creep and shrinkage behavior of a high strength self-compacting concrete is performed. Two new creep and shrinkage prediction models based on the comprehensive analysis on the available models of both conventional concrete and self-compacting concrete are proposed for high strength self-compacting concrete structures. In order to evaluate the predictability of the proposed models, an experimental program was carried out. A concrete which develops 60 MPa within 24 h was used to obtain experimental results. Several specimens were loaded: (i) at different ages and (ii) with different stress-to-strength ratios. Deformation in non-loaded specimens was also measured to assess shrinkage. All specimens were kept under constant stress during at least 600 days in a climatic chamber with temperature and relative humidity of 20°C and 50%, respectively. Results showed that the new models were able to predict deformations with good accuracy, although provided deformations overestimated slightly.

Notation

a and b	constants
c	cement
f'_c	compressive strength
$f_{cm}(t)$	mean value of compressive strength at time t
$f'_{c,28d}$	compressive strength at the age of 28 days
s' and n	parameters that have to be specifically calibrated for each SCC concrete mix by using experimental results
$T(\Delta t_i)$	the temperature (°C) during the time period Δt_i
T_0	1°C
t	temperature-adjusted concrete age
t_0	starting drying concrete age
t_0, t' and t	effective age (days) of concrete at the beginning of drying, at the beginning of loading and during loading respectively
$V_g/V_{g,lim}$	volume of gravel-to-volume limit of gravel ratio
V_s/V_m	volume of sand-to-volume of mortar ratio
V_{sf}/V_s	volume of fine sand-to-volume of sand ratio
V_w/V_p	volume of water-to-volume of powder ratio
w	water
v/s	volume to surface ratio
α	coefficient representing the influence of the cement type
β	represents time dependency of drying shrinkage
γ	coefficient representing the influence of the cement and admixtures type (γ may be 1 when only ordinary Portland cement is used)
Δt_i	the number of days where the temperature T prevails
$\varepsilon'_{as}(t, t_0)$	autogenous shrinkage strain of concrete from the start of setting to age t
$\varepsilon'_{as\infty}$	final value of autogenous shrinkage strain
ε'_{bc}	final value of basic creep strain per unit stress
$\varepsilon'_{cc}(t, t', t_0)$	creep strain
ε'_{cr}	final value of creep strain per unit stress
$\varepsilon'_{cs}(t, t_0)$	shrinkage strain of concrete from age to t
ε'_{dc}	final value of drying creep strain per unit stress
$\varepsilon'_{ds}(t, t_0)$	drying shrinkage strain of concrete from age to t
$\varepsilon'_{ds\rho}$	final value of drying shrinkage strain
$\varepsilon'_{ds\infty}$	final value of drying shrinkage
$\varepsilon'_{sc}(t, t_0)$	shrinkage strain of concrete from age of t_0 to t
ε'_{sh}	final value of shrinkage strain
η	constant related to compressive strength and water content
κ	conventional scalar damage index
μ, λ and α	parameters to be obtained from a least square minimisation procedure
σ'_{cp}	creep stress unit

Introduction

Self-compacting concrete (SCC) basically consists of the same constituent materials as conventional concrete (CC) (cement, water, aggregates, admixtures and mineral additions), but the final composition of the mixture and its fresh properties are different. In comparison with CC, SCC contains larger quantities of mineral fillers, such as finely crushed limestone or fly ash, and in higher quantities of high-range water-reducing admixtures 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. Using SCC can lead to massive labour and cost savings. It is significant to estimate accurately the crucial mechanical properties of this structural material, including creep and shrinkage deformations, to arrive at a safe and economic analysis and design (Aslani and Nejadi, 2012a).

One critical property is creep of concrete. Creep depends on the characteristics of aggregate stiffness and texture, water/cement (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 loading. According to Neville (1996) mostly the hydrated cement paste experiences creep, whereas the aggregate is the only portion that 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, as creep mainly occurs in the cement paste, the main concern is that SCC may exhibit higher creep because of its high paste content.

Another essential mechanical parameter is the shrinkage of concrete. The overall shrinkage of concrete corresponds to a combination of several shrinkages: plastic shrinkage, autogenous shrinkage, drying shrinkage, thermal shrinkage and carbonation (chemical) shrinkage. In designing CC, shrinkage is frequently taken as drying shrinkage, which is the strain associated with the loss of moisture from the concrete under drying conditions because with a relatively high w/c ratio (higher than 0·40) CC exhibits a relatively low autogenous shrinkage $<100 \times 10^{-6}$ (Aslani and Nejadi, 2012b). In contrast, the SCC used in the precast industry, namely for prestressed applications, typically has a low w/c ratio (0·32–0·40). These relatively low w/c ratios, coupled with a high content of binder lead to greater autogenous shrinkage. Such shrinkage increases and is notable in SCC because of the use of finely ground supplementary cementitious materials and fillers. Therefore, both drying and autogenous shrinkage deformations have to be considered in the structural detailing of reinforced concrete and prestressed concrete members (Khayat and Long, 2010).

Aware that SCC usually has a higher paste volume and/or higher sand-to-aggregate ratio to achieve high workability, several researchers have claimed relatively large creep and shrinkage 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). In fact, although mechanical properties of SCC are superior to those of CC, creep and shrinkage of SCC are significantly high (Issa *et al.*, 2005). Among others, Naito *et al.* (2006) also found that SCC exhibits higher shrinkage and creep than CC, which is probably attributable to the high fine aggregate and paste volume in the SCC.

However, Schindler *et al.* (2007) revealed that the shrinkage of SCC is similar to or less than that of CC. When the shrinkage of SCC is compared with that of CC at 112 days, the sand-to-aggregate ratio effect is not significant for the shrinkage of SCC. The creep coefficients of SCC mixtures were also smaller than those of CC at all loading ages. This was attributed to the low w/c ratio.

The different methodology followed to obtain SCC in different countries (Ouchi *et al.*, 2003) and the limited number of studies concerning its long-term behaviour (Mazzotti and Ceccoli, 2009; Mazzotti *et al.*, 2006; Persson, 2001, 2005; Poppe and De Schutter, 2001; Seng and Shima, 2005) make it still unclear if current international standards can also be applied successfully to SCC (Klug and Holschemaker, 2003; Landsberger and Fernandez-Gomez, 2007; Vidal *et al.*, 2005). Moreover, it has not even been assessed if long-term properties can be predicted with reference to conventional mechanical and physical parameters only (such as strength or w/c ratio), or if the adoption of parameters concerning the mix design is needed.

Research significance

It is vital to investigate whether all the assumed hypotheses used to design structures of CC about creep and shrinkage are also valid for high-strength SCC (HSSCC) structures. Thus, the objectives of this study are

(*a*) to review the accuracies of the CC creep and shrinkage prediction models proposed by international codes of practice, including AASHTO (2004, 2007), ACI (1992), AS (2009), CEB-FIB (2012), BSI (2004) and JSCE (2002)
(*b*) to review the accuracies of the SCC creep and shrinkage prediction models proposed by Cordoba (2007), Khayat and Long (2010), Larson (2006), and Poppe and De Schutter (2005)
(*c*) to propose a new prediction creep and shrinkage model based on the comprehensive analysis of the available models and the experimental results database of both the CC and the SCC
(*d*) to verify the predictability of the proposed models on experimental results conducted in a mix composition previously used in the prefabrication of prestressed bridge girders, i.e. a HSSCC loaded at early ages.

Numerical analysis

Based on recent studies by Aslani and Nejadi (2011a, 2011b), the following procedures are used for comparing available CC creep and shrinkage models

- establish an experimental database for creep and shrinkage results
- establish available creep and shrinkage prediction models database
- compare creep and shrinkage models with SCC experimental results database
- propose SCC creep and shrinkage models based on the previous comparisons
- verify proposed SCC creep and shrinkage models with experimental results tests that have been done in this study.

Creep and shrinkage experimental results database

Tables 1 and 2 present a general summary of the creep and shrinkage concrete mixtures included in the database. The database comprises test results from 11 different investigations, with a total of 52 SCC and 11 CC mixtures for creep tests. Also, the database comprises test results from 14 different investigations, with a total of 165 different SCC mixtures and 21 CC mixtures for shrinkage tests. Tables 1 and 2 also include additional information regarding the applied stress to the creep specimens, age of concrete when shrinkage begins (days), final age of the concrete, relative humidity (RH), type of the specimen, type of cement and filler.

Creep and shrinkage models

This paper also assesses the accuracy of seven commonly used international code-type models that are used to predict creep and shrinkage strains. These empirically-based 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 encountered by each model. In this study the accuracy of the creep and shrinkage prediction models proposed by international codes of practice, including AASHTO (2004, 2007), ACI (1992), AS (2009), CEB-FIB (2012), BSI (2004) and JSCE (2002), are compared with the actual measured creep and shrinkage strains.

As shown in Table 4, the AASHTO (2004, 2007), BSI (2004) and JSCE (2002) models provided better prediction of creep data for CC mixture in the experimental database with a coefficient of correlation factor (R^2) of 0·90, 0·89, 0·89 and 0·86 compared with other models. Also, as shown in Table 4, for the SCC mixture in the experimental database, the AASHTO (2004), ACI (1992) and JSCE (2002) models provided better prediction of creep data with a coefficient of correlation factor (R^2) of 0·87, 0·87 and 0·84 compared with other models.

AASHTO (2004), ACI (1992) and JSCE (2002) CC creep models that have conservative predictions for SCC mixtures in the database are different in the certain intrinsic and/or extrinsic variables. As mentioned in Table 3, the AASHTO (2004) creep model does not have any intrinsic factors, but the JSCE (2002) and ACI (1992) creep models have a good consideration of both intrinsic variables (i.e. aggregate type, aggregates/cement ratio, air content, cement content, cement type, concrete density, fine/total aggregate ratio, slump, w/c ratio and water content) and extrinsic variables (i.e. age at the 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, RH, temperature and time drying commences). The modified composition of SCC in comparison with CC influences the creep behaviour of the concrete. Therefore, it is important to include some important variables that have an impact on this behaviour. By considering these variables, the JSCE (2002) creep model has good intrinsic and extrinsic variables.

As show in Table 5, for CC mixture in the experimental database, the AASHTO (2007) and JSCE (2002) models provided a better prediction of drying shrinkage data with a coefficient of correlation factor (R^2) of 0·88 and 0·84 compared with other models. Also, as shown in Table 5, the AASHTO (2007), AS (2009) and JSCE (2002) models provided a better prediction of SCC mixture in the experimental database drying shrinkage data with a coefficient of correlation factor (R^2) of 0·86, 0·83 and 0·80 compared with other models.

The CC shrinkage models of AASHTO (2007) and JSCE (2002) that have conservative predictions for SCC mixtures in the database are different in the certain intrinsic and/or extrinsic variables. As mentioned in Table 3, the AASHTO (2007) shrinkage model does not have any intrinsic factors, but the JSCE (2002) shrinkage model has a good consideration of both intrinsic and extrinsic variables. When compared with the CC, the modified composition of SCC influences the shrinkage behaviour of concrete. Therefore, it is important to involve some important variables that have an impact on this behaviour. By considering these variables, the JSCE (2002) shrinkage model has good intrinsic and extrinsic variables.

Proposed creep model

The comparison of the different models and the experimental database shows that the ACI (1992), JSCE (2002) and AASHTO (2004) models have conservative creep coefficient predictions. In this study, based on required certain intrinsic and/or extrinsic variables for SCC, the JSCE (2002) creep model gives a good approximation of the creep coefficient. Therefore, with the JSCE (2002) creep model as a basis, an attempt is made to formulate some suggestions to include the cement-to-powder (c/p) ratio into the formulas in order to obtain a better prediction of the time-dependent deformations of normal strength and high strength of SCC. These results are shown in Equations 1–10.

1. For the normal-strength SCC with range of applicability (see the denomination of the parameters in the Notation)

Reference	No. of SCC mixtures	No. of CC mixtures	Applied stress to the creep specimens	Final age of concrete: days	RH: %	Type of specimen: mm	Type of cement	Type of filler
Chopin *et al.* (2003)	5	1	40% or 60% of the compressive strength at 28 days	365	50	Cylinder (90 × 280)	CEM I	Limestone
Poppe and De Schutter (2005)	6	0	1/3 of the compressive strength at 28 days	1400	60	Prism (150 × 150 × 500)	CEM I 42·5 R, CEM I 52·5	Limestone
Horta (2005)	6	0	40% of the compressive strength at 28 days	70, 200	50	Cylinder (150 × 300)	CEM I, CEM III	Fly ash and GGBFS
Larson (2006)	1	0	40% of the compressive strength at 28 days	520	50	Prism (101·6 × 101·6 × 609·6) and cylinder (114·3 × 609·6)	CEM III	Limestone
Turcry *et al.* (2006)	3	3	20% of the compressive strength at 7 days	65, 100	50	Cylinder (110 × 200)	CEM I 52·5, CEM II 42·5	Limestone
Cordoba (2007)	4	1	30% of the compressive strength at 28 days	365	50	Cylinder (101·6 × 203·2), (101·6 × 1057·8)	CEM I/II	Fly ash and GGBFS
Heirman *et al.* (2008)	7	1	±1/3 of the compressive strength at 28 days	70	60	Cylinder (120 × 300)	CEM I 42·5 R, CEM III/A 42·5 N LA	Limestone
Oliva and Cramer (2008)	11	4	40% of the compressive strength at 28 days	495	50	Cylinder (152·4 × 213·6)	CEM I	GGBFS
Kim (2008)	4	4	Changeable for each mixture	150	50	Cylinder (100 × 200)	CEM III	Fly ash and limestone
Zheng *et al.* (2009)	7	1	30% of the compressive strength at loading days	150	60	Prism (100 × 100 × 400)	CEM I	Fly ash
Loser and Leemann (2009)	1	1	Changeable for each mixture	91	70	Prism (120 × 120 × 360)	CEM I 42·5 N, CEM II/A-LL 45·2 N	Fly ash and limestone
Total of 71 mixtures	55	16						

Table 1. Creep experimental results database. SCC, self-compacting concrete; CC, conventional concrete; RH, relative humidity; GGBFS, ground granulated blast furnace slag

Reference	No. of SCC mixtures	No. of CC mixtures	Age of concrete when shrinkage begins: days	Final age of concrete: days	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) and 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 (2010)	10	2	1	56	50	Prism (75 × 75 × 285)	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
Güneyisi *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 Type I/II and Type III)	Fly ash
Total of 186 mixtures	165	21						

Table 2. Shrinkage experimental results database. SCC, self-compacting concrete; CC, conventional concrete; RH, relative humidity; GGBFS, ground granulated blast furnace slag

Models		CEB-FIB (2012)	ACI (1992)	BSI (2004)	JSCE (2002)	AASHTO (2004)	AASHTO (2007)	AS (2009)
Intrinsic factors	Aggregate type							
	aggregate/concrete 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							

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

Creep prediction models	CC R^2	SCC R^2
CEB-FIB (2012)	0·41	0·58
ACI (1992)	0·79	0·84
BSI (2004)	0·89	0·80
JSCE (2002)	0·89	0·87
AASHTO (2004)	0·86	0·87
AASHTO (2007)	0·90	0·80
AS (2009)	0·70	0·75

Table 4. Coefficient of correlation factor (R^2) of creep prediction models for conventional concrete (CC) and self-compacting concrete (SCC)

Shrinkage prediction models	CC R^2	SCC R^2
CEB-FIB (2012)	0·70	0·57
ACI (1992)	0·62	0·66
BSI (2004)	0·72	0·55
JSCE (2002)	0·84	0·83
AASHTO (2004)	0·42	0·47
AASHTO (2007)	0·88	0·86
AS (2009)	0·65	0·80

Table 5. Coefficient of correlation factor (R^2) of shrinkage prediction models for conventional concrete (CC) and self-compacting concrete (SCC)

$$45\% \leqslant \mathrm{RH} \leqslant 80\%$$

$$100\ \mathrm{mm} \leqslant v/s \leqslant 300\ \mathrm{mm}$$

$$120\ \mathrm{kg/m^3} \leqslant w \leqslant 230\ \mathrm{kg/m^3}$$

$$0{\cdot}30 \leqslant w/c \leqslant 0{\cdot}65$$

$$f'_{c,28d} \leqslant 55 \text{ MPa}$$

$$260\,\text{kg/m}^3 \leqslant c \leqslant 500\,\text{kg/m}^3$$

1. $$\varepsilon'_{cc}(t, t', t_0) = \sigma'_{cp} \times \varepsilon'_{cr}[1 - \exp\{-0{\cdot}09(t - t')^{0{\cdot}54}\}] \times (0{\cdot}015 + 1{\cdot}35\,(c/p))^{-1} \quad \text{for } c/p < 0.65$$

2. $$\varepsilon'_{cc}(t, t', t_0) = \sigma'_{cp} \times \varepsilon'_{cr}[1 - \exp\{-0{\cdot}09(t - t')^{0{\cdot}54}\}] \times (0{\cdot}015 + 1{\cdot}05\,(c/p))^{-1} \quad \text{for } c/p \geqslant 0.65$$

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

where μ, λ and α are additional parameters to be obtained from a least square minimisation procedure starting from experimental data (Mazzotti and Ceccoli, 2009) $\mu = 0{\cdot}90$, $\lambda = 1{\cdot}80$, $\alpha = 2{\cdot}10$; moreover, the stress function $\sigma(t, t_0)$ is the actual stress/strength ratio, being

4. $$\sigma\,(t, t_0) = \frac{\sigma\,(t_0)}{f_{cm}\,(t)}$$

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

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

where parameters s' and n have been specifically calibrated for each SCC concrete mix by using experimental results previously described (see Table 3). According to the available data, parameters s' and n range from 0·2 to 0·6 and 0·28 to 0·35 respectively (Mazzotti and Ceccoli, 2009). The adoption of function $\sigma(t, t_0)$ allows for the variable rate of increase of mechanical properties to be taken into account, which is particularly important for concretes loaded at early ages. Finally, the non-linear behaviour during the load application has been introduced in Equation 3 according to the conventional scalar damage index $\kappa = 1 - E/E_0$, in which 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 ($0{\cdot}35 f_{cm}(t)$) or medium ($0{\cdot}55 f_{cm}(t)$) applied stress levels respectively

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

7. $$\varepsilon'_{bc} = [17{\cdot}5\,(c + w)^{2{\cdot}0}(w/c)^{2{\cdot}4}\{\ln(t')\}^{-0{\cdot}67}] \times 10^{-10}$$

8. $$\varepsilon'_{dc} = \left[4500\,(w/c)^{4{\cdot}2}\,(c + w)^{1{\cdot}4}\left[\ln\left(\frac{v/s}{10}\right)\right]^{-2{\cdot}2} \times \left\{1 - \frac{\text{RH}}{100}\right\}^{0{\cdot}36} t_0^{-0{\cdot}30}\right] \times 10^{-10}$$

2. For the HS SCC with range of applicability by using Equations 3–5

$$45\% \leqslant \text{RH} \leqslant 90\,\%$$

$$120\ \text{kg/m}^3 \leqslant w \leqslant 230\ \text{kg/m}^3$$

$$100\ \text{mm} \leqslant v/s \leqslant 300\ \text{mm}$$

$$0{\cdot}30 \leqslant w/c \leqslant 0{\cdot}65$$

$$55 \leqslant f'_{c,28d} \leqslant 100\,\text{MPa}$$

9. $$\varepsilon'_{cc}(t, t', t_0) = \sigma'_{cp} \times \left[\frac{4w(1 - \text{RH}/100) + 350}{12 + f'_c(t')}\ln(t - t' + 1)\right] \times (10 \times (c/p)^{0{\cdot}678}) \quad \text{for } c/p < 0.65$$

$$\varepsilon'_{cc}(t, t', t_0) = \sigma'_{cp} \times \left[\frac{4w(1 - \mathrm{RH}/100) + 350}{12 + f'_c(t')} \ln(t - t' + 1)\right] \times (13 \times (c/p)^{0{\cdot}701}) \quad \text{for } c/p \geqslant 0.65 \tag{10}$$

where for t_0, t' and t are replaced by

$$t = \sum_{i=1}^{n} \Delta t_i \exp\left[13{\cdot}65 - \frac{4000}{273 + T(\Delta t_i)/T_0}\right]$$

Proposed shrinkage model

The comparison of the different models and the experimental database shows that the AASHTO (2004), ACI (1992) and JSCE (2002) models have conservative drying shrinkage predictions. In this study, based on required certain intrinsic and/or extrinsic variables for SCC, the JSCE (2002) drying shrinkage model gives the best approximation of the drying shrinkage strain. Therefore, with the JSCE (2002) model as a basis, an attempt is made to formulate some suggestions to include the c/p ratio into the formulas in order to obtain a better prediction of the time-dependent deformations of normal strength and high strength of SCC. These results are shown in Equations 11–17.

For normal-strength SCC (with range of applicability same as creep proposed model)

$$\varepsilon'_{cs}(t, t_0) = \varepsilon'_{sh}\left[1 - \exp\{-0{\cdot}1(t - t_0)^{(-2{\cdot}4(c/p)+2{\cdot}3)}\}\right] \tag{11}$$

$$\varepsilon'_{sh} = \left[-50 + 78\left\{1 - \exp\left(\frac{\mathrm{RH}}{100}\right)\right\} + 38{\cdot}3 \ln w - 0{\cdot}92 \ln\left(\frac{w}{c}\right) - 5\left[\ln\left(\frac{v/s}{10}\right)\right]^2\right] \times (10^{-5}) \quad \text{for } c/p < 0.65 \tag{12}$$

For the HS SCC with range of applicability (with range of applicability same as creep proposed model)

$$\varepsilon'_{cs}(t, t_0) = \varepsilon'_{ds}(t, t_0) + \varepsilon'_{as}(t, t_0) \tag{13}$$

$$\varepsilon'_{ds}(t, t_0) = \frac{\varepsilon'_{ds\infty}(t - t_0)}{\beta + (t - t_0)} \tag{14}$$

$$\varepsilon'_{ds\infty} = \frac{\varepsilon'_{ds\rho}}{\eta t_0}(\times 10^{-6}) \tag{15}$$

$$\varepsilon'_{ds\rho} = \left[\frac{\alpha(1 - \mathrm{RH}/100)w}{1 + 110\exp\left\{-\frac{400}{f'_{c,28d}}\right\}}\right] \times (0{\cdot}015 + 1{\cdot}35(c/p))^{-1} \quad \text{for } c/p < 0.65 \tag{16}$$

$$\varepsilon'_{ds\rho} = \left[\frac{\alpha(1 - \mathrm{RH}/100)w}{1 + 110\exp\left\{-\frac{410}{f'_{c,28d}}\right\}}\right] \times (0{\cdot}015 + 1{\cdot}05(c/p))^{-1} \quad \text{for } c/p \geqslant 0.65 \tag{17}$$

with

$$\beta = \frac{4w\sqrt{v/s}}{100 + 0{\cdot}7t_0},$$

$$\eta = [15\exp(0{\cdot}007 f'_c(28)) + 0{\cdot}25w] \times 10^{-4},$$

$$\varepsilon'_{as}(t, t_0) = \varepsilon'_{as}(t) - \varepsilon'_{as}(t_0),$$

$$\varepsilon'_{as}(t) = \gamma\varepsilon'_{as\infty}[1 - \exp\{-a(t - t_s)^b\}] \times 10^{-6},$$

$$\varepsilon'_{as\infty} = 3070\exp\{-7{\cdot}2(w/c)\},$$

$\alpha = 11$ for normal and low heat cement or $\alpha = 15$ for high early strength cement.

where for t_0, t' and t are replaced by the temperature-adjusted concrete age and γ is a coefficient representing the influence of the cement and admixtures type (may be 1 when only ordinary Portland cement is used). The variations of a and b constants with w/c ratio are given in Table 6.

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

Table 6. Variations of *a* and *b* constants with water/cement (w/c) ratio

Material denomination: kg	
CEM I 42.5R (Portland)	400
Limestone filler	192
Sika viscocrete 20HE	4·7
Natural fine siliceous sand	399
Natural coarse siliceous sand	397
Crushed limestone (washed gravel)	852
Tap water (total)	139·5

Table 7. Mix compositions per cubic meter

Experimental programme

In order to validate the proposed models, an experimental programme with shrinkage and creep tests was carried out in a laboratory. A mix composition previously used in the prefabrication of prestressed bridge girders was used. Bearing aware that in precast/prestress industries it is necessary to apply prestress as soon as possible in order to reduce the time of each production cycle, the concrete used is a SCC that reaches a compressive strength higher than 60 MPa at the age of 24 h. As a consequence, loading could be applied at early ages. In order to verify the predictability of the proposed models in a HSSCC loaded at early ages, in this experimental work specimens were loaded at the ages of 12 h, 16 h, 20 h, 24 h, 48 h and 72 h.

Materials and mix proportions

Cement CEM I 42.5R (BSI, 2000a) with specific gravity of 3·10 and limestone filler with a specific gravity of 2·70 were used. A polycarboxylate type superplasticiser was used, having a specific gravity of 1·08 and 40·0% solid content. The aggregates were dried, and the specific gravities of the coarse aggregate, fine sand and coarse sand were 2·68, 2·63 and 2·62, and absorption values were 1·40%, 0·20% and 0·40%, respectively, according to EN 1097–6:2000 (BSI, 2000b). The bulk density of the compacted gravel was 1·38. The water content was recalculated owing to water included in the superplasticiser and the water required to saturate the aggregates.

The constituent materials used and the corresponding mix proportions are reported in Table 7. Note that the w/c ratio was 0·32, superplasticiser-to-powder ratio was 0·80%, volume of water-to-volume of powder ratio (V_w/V_p) was 0·64, volume of sand-to-volume of mortar ratio (V_s/V_m) was 0·48, volume of fine sand-to-volume of sand ratio (V_{sf}/V_s) was 0·50 and volume of gravel-to-volume limit of gravel ratio ($V_g/V_{g,lim}$) was 0·65.

Mixing, fresh testing and casting

Several batches of 57 l were prepared using a mixer with a vertical axis according to the following sequence

- mixing aggregates and 15% of total water during 2·5 min
- stop mixing for 2·5 min
- adding cement, filler, remaining water and superplasticiser and mixing for 5 min
- stop mixing for 1 min (cleaning mixer paddles)
- mixing for 3 min
- evaluation of the self-compacting properties and casting.

Immediately after mixing was finished, self-compacting properties were evaluated: the slump flow, the V-funnel, the L-box and the segregation tests were carried out according to the European guidelines for self-compacting concrete (EFNARC, 2005). All specimens were cast within 15 min after mixing was finished. After casting was finished, specimens were carefully moved in order to be stored up to the demoulding time in a temperature and RH controlled room (20 ± 0·3°C and 50 ± 3% respectively). All tests were performed using cylinder specimens: specimens with 150 mm diameter and 300 mm height for compressive strength and elastic modulus tests; specimens with 141 mm diameter and 500 mm height for deformation measurements. In order to eliminate the effect of the specimens' surface roughness on the uniaxiality, the top and bottom faces of all specimens were smoothed just after demoulding. A thermocouple was located nearly at the centre of two specimens and to record the temperature over a period of 70 h to allow for maturity corrections.

Deformation measurements

The creep tests were carried out by applying a uniaxial load in two superposed specimens with a flat hydraulic jack, which was able to keep the stress constant throughout the test. Measurements were manually acquired by using a digital extensometer. Each specimen had eight pins divided per four generatrices rotated 90° to each other. Three readings per generatrix were taken (the base of measuring was 200 mm), and the specimen deformation calculated using the average of the four generatrices.

The loads corresponding to 20%, 30% and 40% of the stress-to-strength ratio (at the age of loading) were kept constant for at least 600 days. The first measurement was taken immediately before loading and the second one immediately after loading. In order to evaluate shrinkage deformations, two non-loaded specimens per age of loading were also measured.

Concrete fresh and mechanical properties

All the batches produced presented similar self-compactability and pertained to classes SF3, VS2/VF2, PA2 and SR2 (EFNARC, 2005). The following results were observed: diameter for slump flow was 803 ± 9·7 mm; time for V-funnel test was 18·43 ± 1·06 s; ratio for L-box test was 0·94 ± 0·04; and the segregation was 5·9 ± 2·5%.

The evolutions of the elastic modulus and the compressive strength of measured are summarised in Table 8. Bearing in mind that the mix composition was previously used in the prefabrication of prestressed bridge girders, as expected the concrete strength increased very quickly at early ages reaching almost 50 MPa at the age of 12 h and more than 60 MPa at 24 h. Then, it continued to increase, but at lower rates, reaching nearly 70 MPa at 72 h and 90 MPa at 28 days.

Age	Elastic modulus: GPa	Compressive strength: MPa
12 h	35·6	48·4
16 h	—	55·2
20 h	—	59·9
24 h	39·9	62·3
48 h	—	66·3
72 h	—	69·3
28 d	45·5	91·9

Table 8. Evolution of mechanic properties measured

Deformation results

Results of the total strain (creep strain + shrinkage strain) for all sets of loaded specimens are presented in Figure 1. Analysing Figure 1, it is noted that, roughly speaking, the total strain is similar for all specimens loaded at 30% of the stress-to-strength ratio (the maximum difference was $\sim 150 \times 10^{-6}$). Therefore, one may conclude that the resistance against the deformation increases with strength (note that to keep the stress-to-strength ratio constant, higher loads are applied for higher strengths).

Comparing the total strain of specimens loaded at the age of 12 h with those loaded at the age of 24 h, it was observed that those loaded at the age of 24 h showed higher strain – such a difference

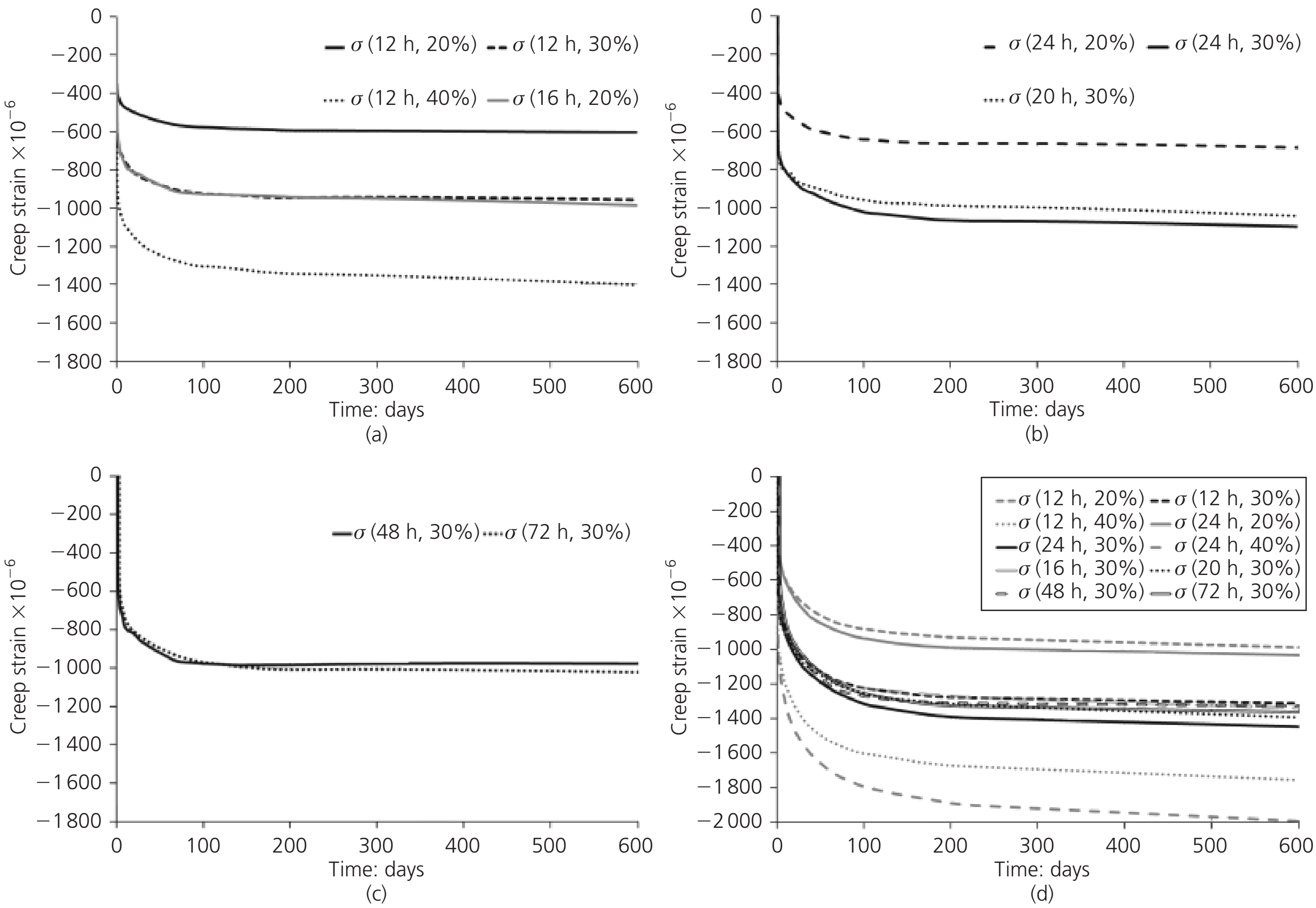

Figure 1. (a) Creep strain for all specimens loaded at 12 h and 16 h, (b) creep strain for all specimens loaded at 20 h and 24 h, (c) creep strain for all specimens loaded at 48 h and 72 h, (d) total strain for all specimens

being higher for greater loads. Thus, one may conclude that, from the age of 12 h to the age of 24 h, the increase of resistance against the concrete deformation is lower than the increase of strength. Furthermore, looking at specimens loaded at the same age, but with different stress-to-strength ratios, it is observed that there is a near linear increase of strain; that is, the total strain of the specimens loaded at the age of 24 h varies (at the age of 600 days) from approximately 1030×10^{-6} to 1450×10^{-6} and then to 2000×10^{-6} when the stress-to-strength ratio varies from 20% to 30% and to 40%. Analogous trends can be observed for specimens loaded at the age of 12 h.

Regarding the shrinkage strain, Figure 2 presents evolution curves for the deformation of non-loaded specimens. Analysing the measured curves, one observes a rapid evolution for approximately 200 days. However, after that age, the shrinkage increases by only about 10%. According to the results shown in Figure 2, generally speaking, a consistent tendency relative to the age of demoulding (as previously reported in Bissonnette and Pigeon (1995) and as suggested by several models) is not observed. In fact, the specimens demoulded at the age of 12 h and at the age of 72 h are the ones with the lowest shrinkage, while the ones demoulded at the age of 16 h are the ones with the highest.

Predictability and discussion of the proposed models

Proposed creep and shrinkage models are useable for lower and higher c/p, and are adjusted to the normal and HSSCC. A non-linear creep amplification function (Equation 3) is added to the creep model, which shows an influential stress function on the creep behaviour. The proposed creep model is adjusted to normal and HSSCC. Furthermore, SCC loading age parameter is included in the creep model as given by Equation 5.

However, before analysing the predictability of the proposed models, it is important to remember that although shrinkage and creep are not totally independent phenomena (Bažant *et al.*, 1994; Neville *et al.*, 1983; Reinhardt and Rinder, 2006), in this experimental programme the total strain was roughly understood as

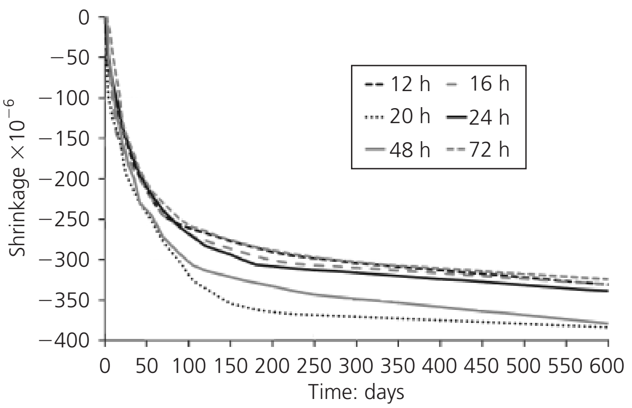

Figure 2. Shrinkage evolution

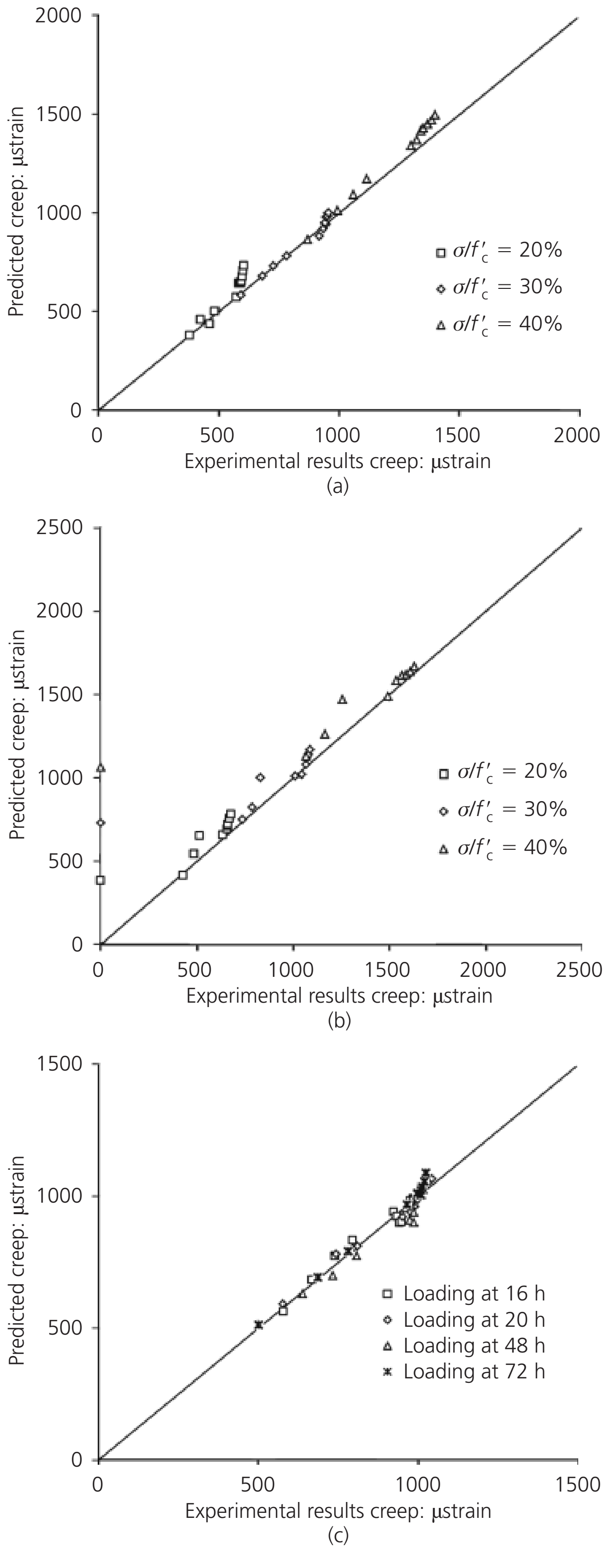

Figure 3. Comparison of the self-compacting concrete creep from experimental results versus calculated values from proposed model for (a) 12 h with different loading percentages, (b) 24 h with different loading percentages and (c) 30% loading rate for 16, 20, 48, and 72 h

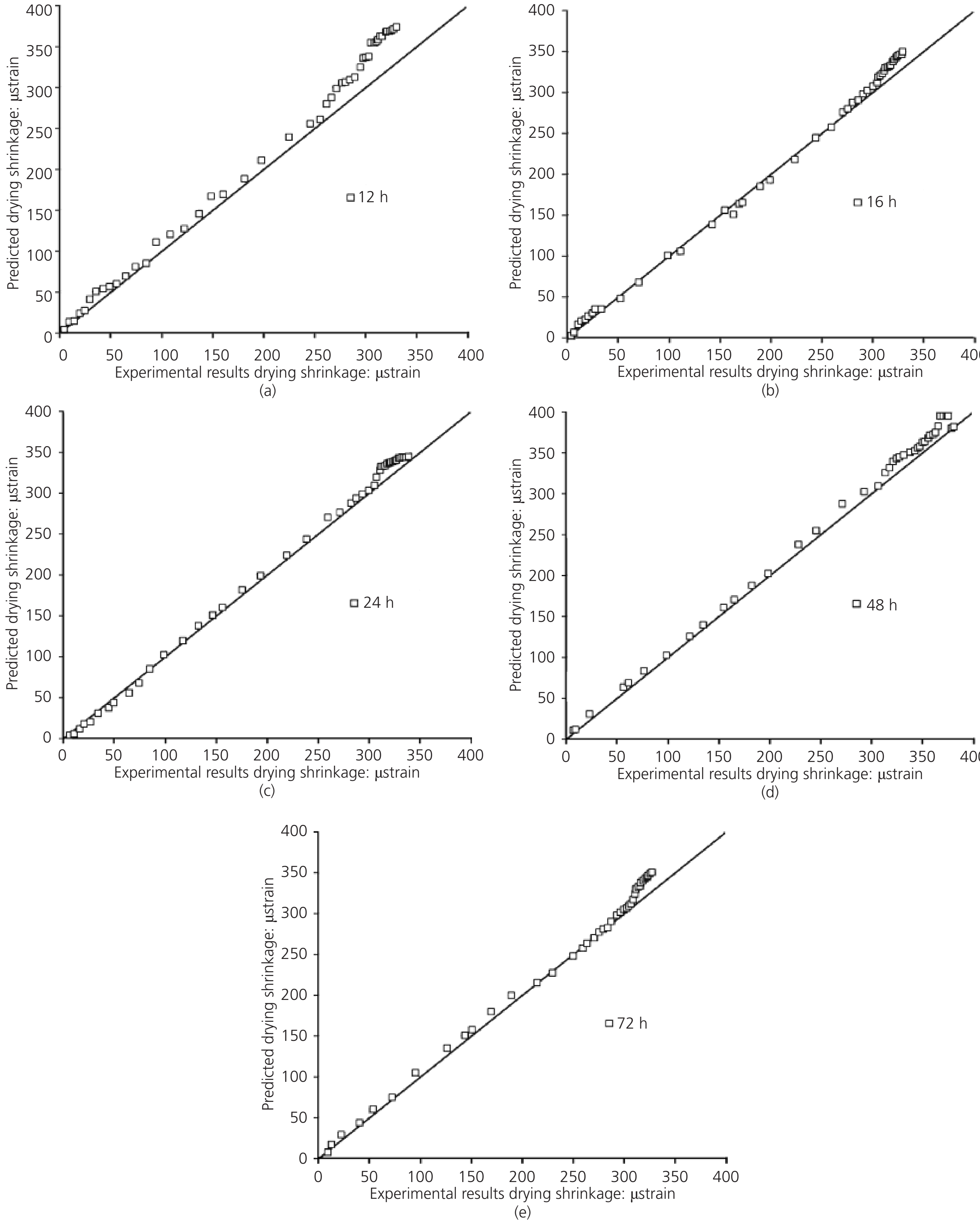

Figure 4. Comparison of the self-compacting concrete drying shrinkage from experimental results versus calculated values from proposed model for (a) 12 h, (b) 16 h, (c) 24 h, (d) 48 h and (e) 72 h

composed of the addition of these independent phenomena. Consequently, experimental results of creep strain used to verify the predictability of the proposed creep model were determined as the difference between the total strain and shrinkage strain (CEB-FIB, 2012; Leemann *et al.*, 2011; Reinhardt and Rinder, 2006). Besides, according to the experimental data reported above, the following parameters were considered in the predictability of the proposed models: RH = 50%, $w = 128\ \text{kg/m}^3$, $c = 400\text{kg/m}^3$, $w/c = 0{\cdot}32$, $v/s = 141$ mm, $c/p = 67{\cdot}6\%$ and $f'_{\text{cd,28d}} = 91{\cdot}9$ MPa.

Figure 3 shows a comparison of the proposed creep model with the available experimental results of creep. In analysing Figure 3 one observes that the proposed model provides an accurate prediction. In fact, most of the creep results predicted by the proposed model were slightly overestimated, but always with a difference lower than 10% to the experimental results.

Figure 3 shows a comparison of the SCC creep from experimental results plotted against calculated values from the proposed model for (a) loading at the age of 12 h with different levels of the stress-to-strength ratios loading percentages, (b) loading at the age of 24 h with different levels of the stress-to-strength ratios loading percentages, and (c) 30% loading at the age of loading rate for 16, 20, 48 and 72 h with a level of 30% of the stress-to-strength ratio. Based on the results and comparisons reported in Figure 3, the proposed creep model was accurate for different levels of stress and different ages at loading time. In fact, most of the creep results predicted by the proposed model were slightly overestimated, but always with the difference being lower than 10% of the experimental results.

In terms of the proposed shrinkage model, Figure 4 shows a comparison of the SCC shrinkage from experimental results against calculated values from the proposed model for (a) 12 h, (b) 16 h, (c) 24 h (d) 48 h and (e) 72 h. Looking at Figure 4, roughly speaking, it can be noted that the proposed model provided a good prediction (especially up to the age of 100 days). The predicted results were mostly conservative (especially after the age of 300 days), the maximum difference (~20%) between predicted and experimental results occurring when specimens were demoulded at the age of 12 h (Figure 4(a)).

Conclusions

The predictability of deformation models have been investigated for CC and SCC in this paper. Two new models are proposed for an accurate prediction of creep and shrinkage for concrete structures made with HSSCC. Based on comparisons between different models and on comparisons to the experimental results, some conclusions can be drawn from this study.

- For the CC mixtures the AASHTO (2007) and JSCE (2002) models provided better predictions of the creep and shrinkage data compared with the other models. Although the BSI (2004) and AASHTO (2004) models had provided suitable predictions for creep, they were not so successful for shrinkage.
- For the SCC mixtures the JSCE (2002) model provided better predictions of the creep and shrinkage data than the other models because of the certain intrinsic and/or extrinsic variables. The AASHTO (2004) and ACI (1992) CC models also provided suitable predictions for creep, and the AASHTO (2007) and AS (2009) CC models also provided suitable predictions for shrinkage.
- The proposed creep and shrinkage models have good predictions for high strength of the SCC mixtures. The comparison between the predicted values and the experimental results conducted in this study showed that the proposed models were able to predict creep and shrinkage with an accuracy of 10% and 20% respectively.

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