An Experimental Campaign on the Long-Term Properties of Self Compacting Concrete

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(Received: 22 February 2011; Received revised form: 24 September 2011; Accepted: 4 October 2011)

Abstract: In the present paper, the results of an experimental campaign concerning the long-term properties of self-compacting concrete are presented. Five mixes of SCC and one mix of CVC have been employed, with different compressive strength covering the range of application from cast-in-place to prestressed structures.

For each mix, compressive strength, elastic modulus and shrinkage evolution with time have been monitored. Creep tests have also been performed at different stress levels and at two ages at loading (7 and 28 days). The influence of concrete strength, stress level have been observed, together with the role played by the mix parameters. The Poisson' ratio evolution with time has been also observed; the role played by the application of long term loads and by different curing conditions on the concrete residual strength has been also investigated.

Finally, experimental data both in terms of shrinkage and creep are compared with international code provisions.

Key words: self-compacting concrete, experimental tests, creep, shrinkage, non-linear behaviour, Poisson's ratio, elastic modulus.

1. INTRODUCTION

During the last two decades, the introduction of the self-compacting concrete (SCC) in the construction industry has posed a valuable alternative to the conventional vibrated concrete (CVC). Its fresh-state properties, like the self-compactability, the ability to flow for long distances, even in tight spaces, and the quality of the finished surfaces, make the SCC an ideal material in many circumstances, especially in the precast industry.

The SCC is produced in different countries mainly according to three different mix-design criteria (Lachemi *et al*. 2003; Heirman *et al*. 2008) to obtain the required segregation resistance. The three leading types of SCC are: (*a*) powder type SCC, with a total powder content of about 550–650 kg/m^3, (*b*) combination type SCC, using a viscosity modifying agent (VMA) and filler and with a total powder content of about 450–550 kg/m^3, (*c*) viscosity modifying agent type SCC, with VMA only and a total powder content of about 350–450 kg/m^3. Moreover, the production of the same type of SCC in the different countries can be characterized by very different levels of viscosity, even if the workability (slump flow) is similar (Ouchi *et al*. 2003), or by using different types of powder components (Hossain and Lachemi 2010). Due to these relevant differences in the mix-design philosophy, the mechanical and rheological properties of the SCC may be quite different and a clear and systematic knowledge of all its properties is not presently available; in confirmation of this, the RILEM association has recently set up a Technical Committee devoted to the systematic classification of the mechanical properties of the SCC as a function of its constituents.

Among the different mechanical properties (strength, elastic modulus, toughness, etc…), probably creep and shrinkage of SCCs are those which require to be better and more systematically investigated. For the creep in

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Associate Editor: J.G. Dai.

particular, due to the limited number of studies at the material (Persson 2001, 2005; Viera and Bettencourt 2003; Poppe and De Schutter 2005; Seng and Shima 2005; Mazzotti *et al*. 2006; Heirman *et al*. 2008, Leemann *et al*. 2011) and the structural level (Craeye *et al*. 2009; Mazzotti and Savoia 2009), the role played by the different components has not been clarified yet. It is also still not known if the prediction by the current International Standards apply successfully also to the SCCs (Klug and Holschemaker 2003; Vidal *et al*. 2005; Landsberger and Fernandez-Gomez 2007). Moreover, it has not been even assessed if the long-term properties of the SCCs can be predicted as a function of conventional mechanical and physical parameters only (like strength, *w*/*c*,…) or additional parameters concerning the mix-design are strongly needed.

In this framework, the University of Bologna has been involved in a National Research Project aimed at investigating the mechanical and structural properties of the SCC, in particular of powder type and combination type SCCs; in Italy and good part of Europe, in fact, these are the most common types of adopted SCC. In particular, limestone filler type SCC covers most of the applications, due to large availability of this type of filler. In the present paper, the results of the experimental campaign concerning the long-term properties of the hardened SCC are presented, together with their comparison with recognized prediction models and guidelines mainly based on engineering parameters like compressive strength. In this perspective, the research provides for some experimental results describing the variability of the considered long-term properties when key-engineering parameters are changed and clarify the over-simplification of most available numerical tools when trying to predict the long-term behaviour of modern SCC concrete mixes.

In more details, five mixes of SCC have been cast, with different compressive strengths (the main parameter adopted in European standards to identify the concrete classes), i.e. from *C*30/37 to *C*55/67. For each mix, the compressive strength, the elastic modulus evolution with time and the shrinkage behaviour have been monitored along a period of time of about one year (for further details, see Mazzotti *et al*. 2008).

As for the creep tests, different sustained stress levels (between 35% and 65% of the compressive strength at the age of loading) have been applied to cover the range of the applications from cast-in-place to prestressed structures, and to verify if the conventional stress limits for linear viscoelasticity can still be applied to SCC elements. Two different ages at loading (7 and 28 days) have been considered. The effect of the sustained load and of the different aging conditions on the compressive strength has been also investigated, together with the Poisson's ratio evolution with time during the creep tests.

Finally, the experimental data, both in terms of shrinkage and creep, have been compared with the prediction models provided by the most important international codes and guidelines and with recognised models reported in the literature.

2. MATERIAL PROPERTIES

In order to compare the rheological properties of SCCs with different strengths, a series of mixes ranging from normal to medium strength have been prepared. A conventional vibrated concrete (CVC) with medium strength has been also tested and the results compared with a SCC with similar strength. A detailed description of the mix compositions adopted is reported in Table 1, whereas the main mix parameters (water/cement *w*/*c*, water powder *w*/*p*, filler replacement *f*/*p* and paste volume v_p) and the fresh-state

Table 1. Mix composition of SCC and CVC mixes

Component	Type	Unit	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6 CVC
Cement	32.5 II AL	kg/m^3	355	360	–	–		410
Cement	42.5 II AL	kg/m^3	–	–	440	–		–
Cement	52.5 I N	kg/m^3	–	–	–	440	–	–
Cement	52.5 I R	kg/m^3	–	–	–	–	400	–
Filler		kg/m^3	199	173	110	110	100	–
Fine sand	0–4 mm	kg/m^3	968	863	826	826	675	751
Coarse sand	8–12 mm	kg/m^3	470	550	520	520	340	567
Gravel	12–25 mm	kg/m^3	182	181	240	240	800	452
Superplast.		l/ m^3	6.30	8.70	6.75	6.75	4.4	4.51
VMA		l/ m^3	0.70	0.90	0.75	0.75	1.0	–
Water		l/ m^3	173	205	204	209	180	174

Table 2. Water/cement (*w/c*), water/powder (*w/p*), filler/powder (*f/p*) ratios and paste volumes (v_p) of SCC and CVC mixes

Properties	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6 CVC
w/c	0.48	0.57	0.46	0.47	0.45	0.42
w/p	0.31	0.39	0.37	0.38	0.36	0.42
f/p	0.40	0.36	0.23	0.23	0.23	–
v_p (l/m^3)	366	393	392	397	350	309

Table 3. Fresh properties of SCC and CVC mixes

Test	Unit	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6 CVC
Slump flow	cm	79	79	78	66	65	18
V-funnel	s	7.6	–	5.2	5.0	7.1	–
J-ring	cm	75.5	–	77.5	62	61	–

properties (flow cone, J-ring and V-Funnel tests, measured according to Italian Standard UNI 11040) are reported in Tables 2 and 3, respectively; for the CVC mix, the classical slump measure is reported. Mix 5 is specifically designed for the precast industry, having a smaller *w/c* ratio and a large solid skeleton (800 kg/m^3 of gravel); its long–term deformation, as will be shown in the following, will be also strongly reduced. The SCCs have been cast with different types of cement (type I and II), paste volume ranging from 350 to 397 l/m^3, the level of cement replacement with filler *f/p* ranging from 0.23 to 0.40 and *w/p* ratio ranging from 0.31 to 0.39; furthermore, mix 1 has a lower water content. From the fresh-state tests, the mix 1 exhibited higher viscosity and filling ability.

The experimental tests have been conducted on cylinders. After demolding, all the specimens have been cured at RH = 60% and T = 20°C, except for mixes 1, 5 and 6, whose cylinders have been stored at RH = 98% until one day prior to the tests.

3. STRENGTH AND ELASTIC MODULUS EVOLUTION WITH TIME

The strength and the elastic modulus evolution with time of all the mixes have been investigated (according to EN 12390-3 and UNI 6556, respectively) by compressive tests on 100 × 200 mm ($\phi \times h$) cylinders at different aging times; the 28-day mean compressive cylindrical strength f_{cm} of mixes 1 to 6 was 42.6, 34.3, 40.1, 57.9, 54.1 and 47.8 MPa, respectively. The experimental results on the strength variation with time have then been compared with the provisions by Model Code 1990 (CEB-FIP 1990), the reference model for all types of concretes at an European level, according to the equation:

$$f_c\left(t_0\right) = f_{ci}\, e^{s\left(1-\sqrt{\frac{28}{t_0}}\right)} \tag{1}$$

where t_0 is the age of concrete (days), s a parameter depending on the type of cement (s = 0.25 in the present case) and f_{ci} the 28-day cylindrical compressive strength (mean value obtained from tests, i.e. $f_{ci} = f_{cm}(28)$). The comparison reported in Figures 1(a) to 1(c) for mixes 1–2, 3–4 and 5–6, respectively, shows that the theoretical formulation, originally defined for standard concretes, is able to reproduce quite well the strength increase of all the SCC mixes up to 90 days; after that time, the code provision suggests a negligible strength increase (5% from 3 to 6 months), whereas for some mixes (1 and 3) the strength increase was significantly higher (about 15%). This is probably due to the higher amount of filler (90% limestone and 10% fly ash) for mix 1 and to the type of cement and the amount of filler for mix 3. Even though no general conclusions can be drawn due to the limited number of tests, analogous results can be found in the literature (Persson 2001). The strength increase of the SCC mixes after 3 months may have a significant role also on the creep effects, as will be explained in the following.

Moreover, the strength increase with time of mixes 4, 5 follows more regularly the code provisions and, after few months of aging, the strength increase is

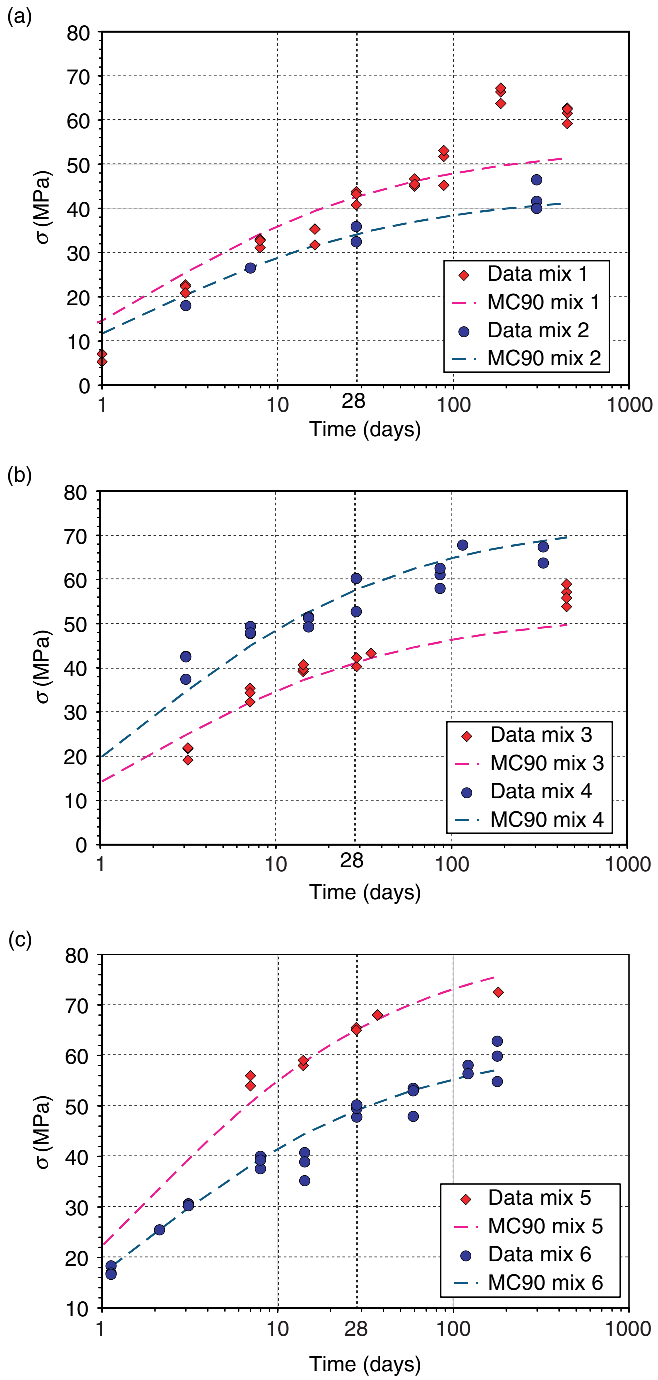


Figure 1. Time variation of compressive cylindrical strength of mixes (a) 1, 2; (b) 3, 4; and (c) 5, 6, compared with provisions by CEB MC90

significantly reduced; the early attainment of high strength values is a well-known consequence of the adoption of the 52.5 type cement.

In Figure 1(c), the comparison between the experimental results from mix 6 (CVC) and the MC90 provisions is also reported; in this case, the numerical model is able to correctly follow the strength evolution with time obtained experimentally.

Figures 2(a), 2(b) show the elastic modulus of all the mixes at different aging times compared with the provisions by MC90 according to equation (CEB-FIP 1990):

$$E_c(t_0) = E_{ci}\sqrt{e^{s\left(1-\sqrt{\frac{28}{t_0}}\right)}} \tag{2}$$

where s and t_0 are those previously defined. According to MC90, the elastic modulus E_{ci} has been obtained from the experimental value of the 28-day cylindrical compression strength. Even though some scatter of the experimental results is present, the Figures show that the predictions of the evolution with time of the elastic modulus of medium strength mixes are quite accurate, while the analogous predictions for medium strength mixes (mix 4) slightly overestimate the experimental findings. On the contrary, the time evolution of the elastic modulus of the CVC is properly described. This is due to the amount of the coarse aggregate usually adopted for the SCCs, smaller with respect to that

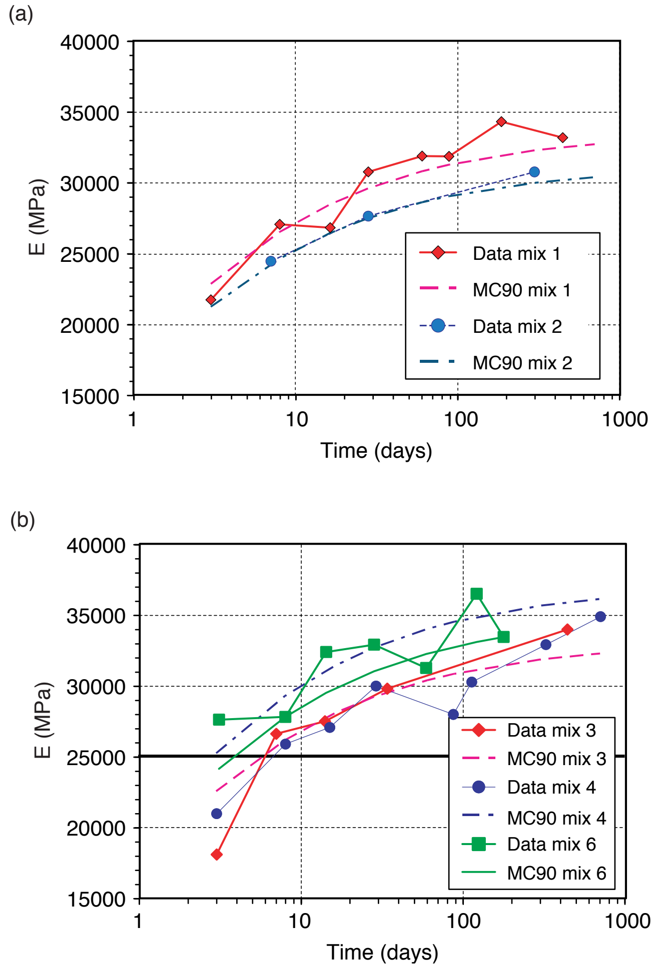


Figure 2. Elastic modulus of mixes (a) 1, 2; and (b) 3, 4 and 6, compared with provisions by CEB MC90

typical of the CVCs included in the database adopted for the calibration of the Model Code predictive law.

4. SHRINKAGE AND CREEP DEFORMATION

4.1. Experimental Set-Up and Instrumentation

The delayed deformations of the SCC mixes have been investigated by performing tests on cylinders with 2 different sizes, 98 × 200 mm ($\phi \times h$) and 122 × 250 mm. For all the mixes but mix 5, four cylinders (two for each diameter) have been used for creep tests (according to ASTM C-512-02) at two different ages at loading and three cylinders 98 × 200 mm ($\phi \times h$) for the shrinkage tests (UNI 6555). For the specimens from mixes 2, 3, 4 and 6, after a curing period of 2 days, the specimens subject to creep tests have been exposed to RH = 60%, T = 20°C climate conditions and loaded at an age of 7 and 28 days from casting, for a period of at least one year by using steel loading frames (described in Mazzotti *et al.* 2008). The specimens from mix 1 and 5 have been wet cured until four days before loading.

Two different diameters of cylinders have been adopted in order to prescribe, within the same steel frame, two different stress levels: about 35% and 55% of the compression strength at the loading time $f_c(t_0)$ for mixes 1 to 4 and 6. The first stress level can be thought to produce creep strains within the framework of linear viscoelasticity, whereas in the second case a non-linear behaviour is expected. The cylinders from mix 5 have been loaded only at one stress level ($0.32 f_{cm}$) and at one age at loading (28 days).

The creep strains (composed of basic and drying creep contributions) have been measured by using couples of longitudinal electrical strain gauges, though the mean strain value only has been recorded and considered in the following. One specimen for each stress level has been instrumented with two additional transverse strain gauges. The specimens subjected to the shrinkage tests have been instrumented similarly; the total shrinkage (composed of autogenous and drying shrinkage contributions) has been measured starting three days after casting for mixes 1, 3, 4, 6, whereas for mix 2 the shrinkage has been measured starting after 7 days from casting.

4.2. Results from Shrinkage Tests

In order to reduce the experimental data scattering, the mean values of the experimental results obtained from the two specimens loaded under identical conditions are reported in the following.

The longitudinal total shrinkage mean strains from all the mixes (measured starting 3 days after casting except for mix 2) are reported in Figure 3. The mixes 3 and 4 show remarkably higher values of the total shrinkage with respect to mix 1; this is due to the type of cement

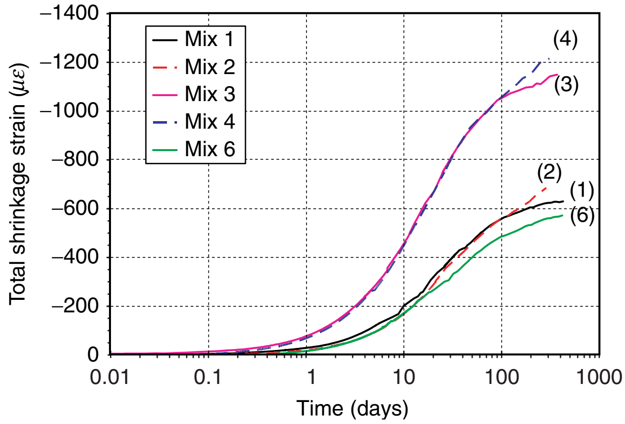


Figure 3. Total shrinkage strains of all mixes

adopted (42.5 and 52.5 instead of 32.5) and to the greater paste volume. The shrinkage strain of mix 2 is smaller with respect to the other mixes, even though its paste volume is comparable with mix 3 and 4, because the measures started only 7 days after casting. Moreover, more than one year after casting, the rate of increase of the shrinkage strain is almost negligible for the mixes 1 and 6, while the mixes 2, 3 and 4 still shows a significant rate of increase (due to larger paste volume). The shrinkage strain of all the SCC mixes was greater than the one recorded from the CVC (mix 6). In particular, the difference between the CVC and the mix 1 is quite small whereas it is greater with respect to the other SCC mixes (mix 2 included because the shrinkage measurement started later respect to the other mixes).

4.3. Results from Creep Tests

For all the mixes loaded at 7-day age from casting, the specific creep functions $C = (\varepsilon_v/\sigma)$ (ε_v and σ being the creep strain and the applied stress) at low and high stress levels ($0.35 \cdot f_{cm}$ and $0.55 \cdot f_{cm}$) are given in Figures 4(a) and 4(b), respectively. The adoption of the specific creep function allows for the direct comparison of creep curves obtained by using different compression stresses (Bazant 1988), which is the present case. In Table 4, the concrete strength f_{cm} for each mix at the time of loading is reported. The shrinkage strain (obtained from the shrinkage tests on the same concretes, see the previous section) has been subtracted in order to consider the creep contribution only. After about one year of loading, the creep strain of mix 1 was smaller with respect to mix 4, at both stress levels; in particular, the mix 4 showed an higher rate of increase during the whole test duration and the specific creep curve exhibited the change of convexity (with the time expressed in log scale) later with respect to mix 1. The differences between the slopes of the curves are probably related with the different strength evolution with time of the two different mixes

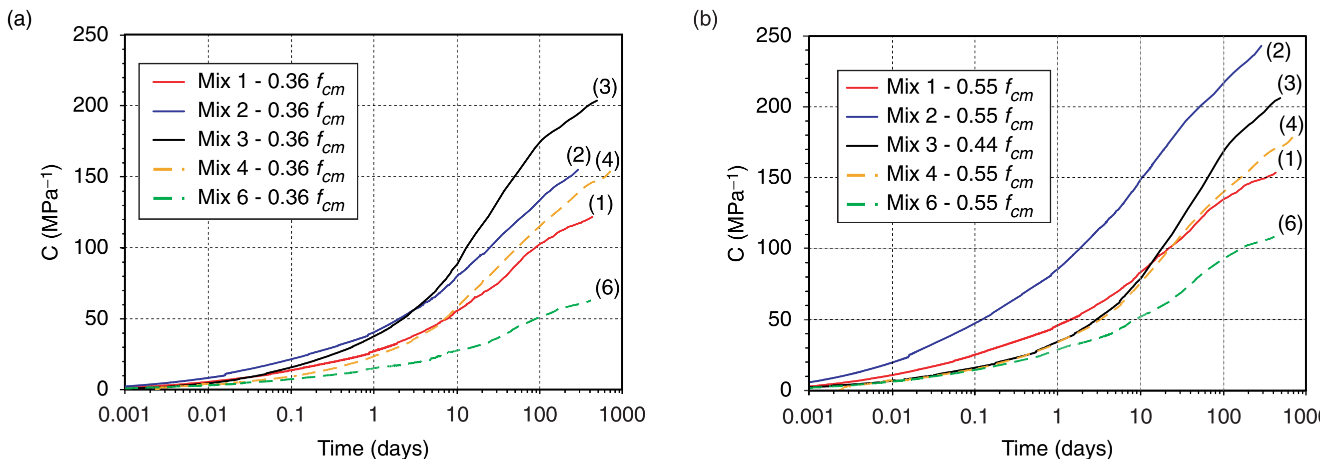


Figure 4. Specific creep of all mixes at (a) low and (b) high stress levels for 7-day age at loading

Table 4. Compressive strength of concrete mixes at the time of loading t_0

	Compressive strength (MPa)					
	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6 CVC
$t_0 = 7$ days	32.20	26.50	33.50	49.63	–	48.70
$t_0 = 28$ days	42.62	34.34	40.05	57.85	65.20	–

(see Figure 1). Mix 1, in fact, exhibited a slower strength increase in the first month after loading but showed an appreciable strength increase after several months after loading. On the contrary, mix 4 attained very rapidly (within 2 months) its final compressive strength (due to the type of cement used). The constant load application, caused the concrete internal *compaction* (a mechanism of strength/stiffness enhancement due to the presence of a moderate permanent load, named *adaptation* in Bazant and Kim 1979) which reduced the delayed creep strains.

The different creep behaviour of the four concretes can be also explained by considering the different mix-designs (Table 1). Mix 1 respect to mix 4 has a smaller paste volume (about 366 *vs* 397 l/m^3) and an higher cement replacement with limestone filler (which should increase the creep according to Poppe and De Schutter 2005); nevertheless, the mix 4 has a greater creep strain; this last consideration suggest that the paste volume has a far more greater influence on the creep behaviour respect to others mix parameters. Furthermore, comparing the creep behaviour of mixes 2 and 4, it can be observed that the mix 2 has w/p ratio and paste volume similar to those of mix 4 but it has an higher cement replacement f/p and a CEM II/A-L cement type, with further addition of limestone powder; all these aspects lead to higher creep strain. For the same reason (the adoption of a type II cement with limestone addition and a different strength class 42.5 *vs* 52.5), also the mix 3 has higher creep with respect to the mix 4, although all the other parameters are similar.

All the SCC mixes exhibited higher values of creep with respect to the CVC (mix 6); far from being a conclusive results, this comparison shows that reducing the fraction of the coarse aggregate in favour of the finest one and of the filler, the concrete is subjected to a more pronounced creep behaviour (mix 1 *vs* mix 6) (Seng and Shima 2005).

For mix 3, the basic creep behaviour has been also investigated subjecting also sealed specimens to long-term compression tests: Figure 5 shows the specific total creep and basic creep curves obtained from the specimens loaded at 7-day age at low stress level ($0.35 \cdot f_{cm}$). The qualitative behaviour of the basic creep is similar to that of the conventional concrete (Bazant and Wittmann 1982; Bazant 1988; Granger and Bazant 1995) and it is almost linear (in the log-scale of time) after one week of constant loading; on the contrary, the total creep curve shows a change in slope (smaller strain rate) after about three months of loading due to the reduction of the drying creep contribution related with the humidity exchange with the surrounding ambient.

The long-term behaviour of the SCC specimens loaded at low stress levels at an age of 28 days is reported in Figure 6(a). As expected, the specific creep of the mixes 1 to 4, after about one year of loading, is

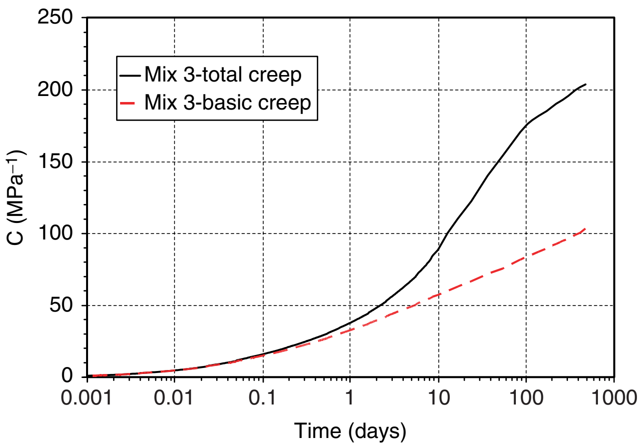


Figure 5. Mix 3: total and basic creep

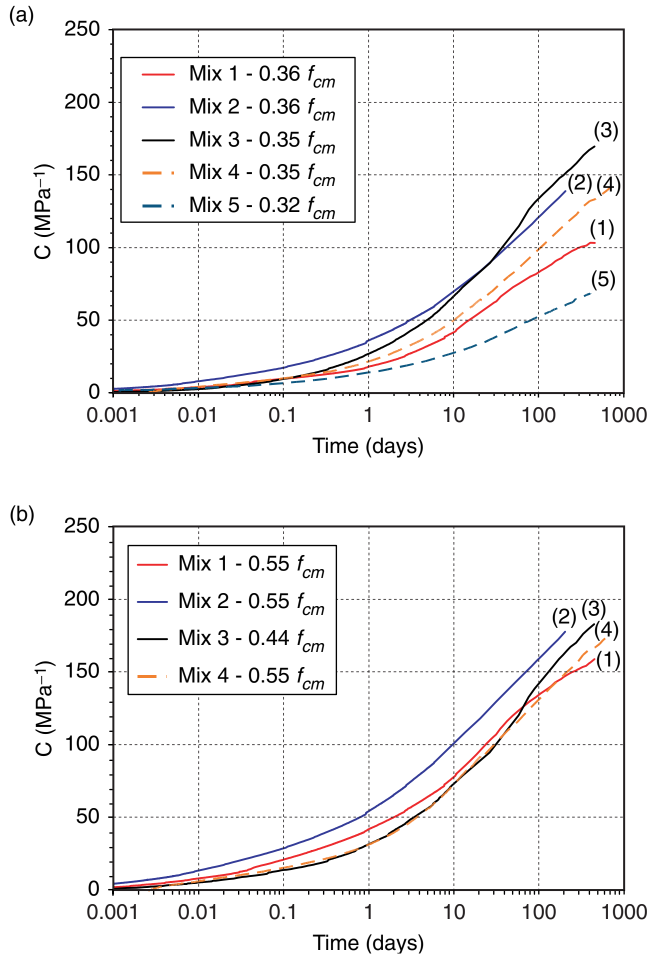


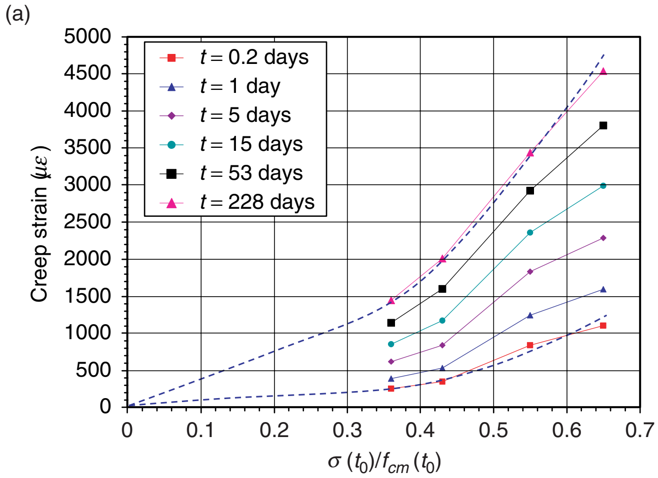
Figure 6. Specific creep of all mixes at (a) low; and (b) high stress levels for 28-day age at loading

smaller with respect to the 7-day age at loading case, but the proportions between the creep values of the various mixes loaded at 28- and 7-day after casting are similar. Mix 5 specimens have the smallest specific creep values, but the change of the slope of the curve is not evident (in the log-scale of time) after few months of loading; this is probably due to the type of the cement (R–rapid hardening) which produces a very rapid concrete aging and to the high amount of coarse aggregate reducing the overall creep behaviour. The reduced creep can be also explained (Heirman *et al.* 2008; Viera and Bettencourt 2003; Loser and Leemann 2009) by considering that with a w/p ratio similar to those of the other mixes, mix 5 has the smallest paste volume (350 l/m^3). Moreover, the difference between creep of mixes 3 and 4 is actually reduced respect to the 7-days case because with greater age at loading the effect of the type of cement is reduced.

Figure 6(b) shows the specific creep curves obtained at high stress level (0.55 f_{cm}) from specimens loaded at 28-day age. The non-linear amplification of the creep function C at higher stress levels is more pronounced with respect to the younger concrete [see Figure 4(b)]: after one year of loading, for mix 1 the non-linear amplification is about 1.3 for the specimens loaded at 7 days and 1.5 for the specimens loaded at 28 days: the smaller non-linear creep behaviour observed at high stress levels for the younger concrete, apparently counterintuitive, can be again considered as an effect of the concrete compaction (Mazzotti *et al.* 2005): the greater improvement with time of the mechanical properties (strength and stiffness), enhanced by the constant stress application, allows for a reduced creep behaviour.

The non-linear creep behaviour of the SCC has been also investigated by considering different long-term stress levels, ranging from 35 to 65% of the compression strength at the time of loading application. Figures 7(a) and 7(b) show the creep strain at increasing times under loading *vs* the applied stress level for mixes 2 and 4, respectively, loaded 7 days after casting. Each curve collects the creep values corresponding to different specimens but recorded after the same time from the initial loading. Moreover, in both figures, two qualitative limit curves for very short and large times of loading are indicated. They suggest an initial linear behaviour followed by a non-linear creep strain increase starting from a stress level σ/f_{cm} of about 0.35–0.40. According to this type of graph, when experimental points deviate from the linear distribution, a non-linear relationship between applied stress and the corresponding creep strain, given a certain time under loading, has to be considered (Smerda and Kristek 1988). This result is in agreement with the well-recognized stress limit of linear viscoelasticity for standard concretes (Neville 1970; CEN 2004) which appears to be valid also for the young SCC concretes ($t_0 = 7$ days) subjected to testing.

The mix 4 shows a more pronounced non linearity, probably due to its higher compression strength



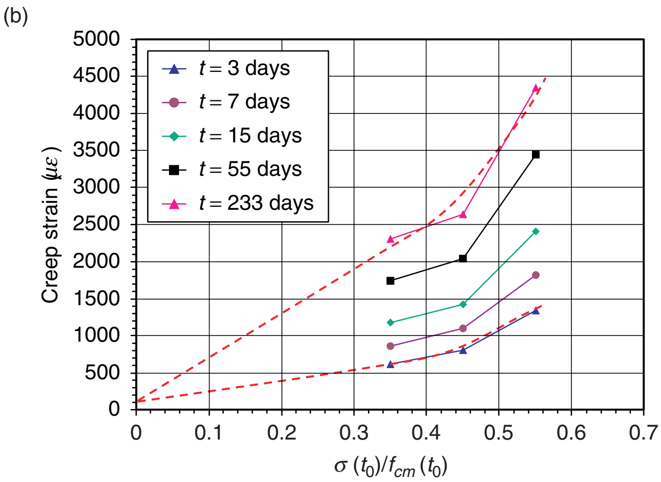


Figure 7. 7-day age at loading: creep strain *vs* applied stress at different times after initial loading for mixes (a) 2; and (b) 4

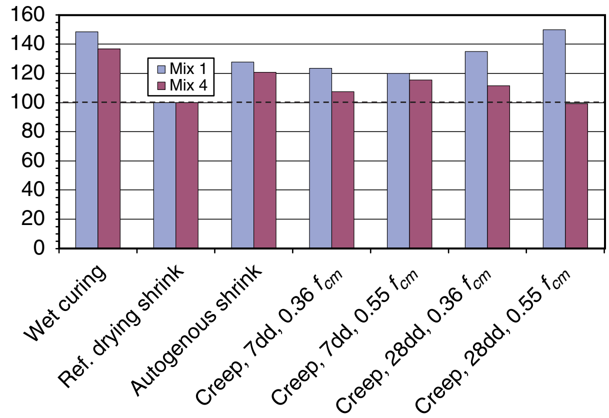


Figure 8. Strength variation due to aging and loading conditions

(obtained using a cement type I, 52.5) attained very rapidly (most of it reached before loading), so reducing the compaction phenomena induced by the constant stress application.

4.4. Effect of Aging and Sustained Load on the Residual Strength

At the end of the creep and shrinkage tests, all the specimens from mixes 1 and 4 have been unloaded (if it was necessary) and subsequently subjected to instantaneous compression tests till failure (following the same standards previously indicated). The obtained values have been considered like the residual strength, useful in order to evaluate the effect of the sustained loading, the different aging conditions (drying or sealed specimens) and the different composition on the long term strength. The Figure 8 shows the compression strength of the specimens subjected to different loading and aging conditions over the strength of the same concretes exposed to the lab environment conditions (T = 20°, RH = 60%) but never loaded (the reference results). All the specimens have been tested after about 400 days from casting. The results reported are the mean values of at least two tests. As expected, the specimens never loaded and subjected to the wet curing (T = 20°, RH = 98%) provided for the highest strength, about 40 percent greater than the reference specimens exposed to the lab environment (T = 20°C and RH = 60%). The sealed specimens (never loaded) do not exchange humidity with the external environment and the strength improvement over the reference case is 15–20 percent. The drying specimens exposed to the lab environment and subjected to the long-term loading after 7 days from casting (both at low and medium stress level) show a strength increase of about 10–15 percent over the unloaded reference specimens (in the same climatic conditions). For the specimens loaded later (28 days from casting), the same behaviour can be observed, except for the medium strength concrete (mix 4), showing no strength increase after the long-term loading at medium stress level. Both phenomena can be traced back to the compaction process, more evident when the load is applied at an early stage of the concrete aging (Bazant and Kim 1979). In conclusion, the effects of the sustained loading on the residual strength of the SCC can be considered similar from the qualitative point of view to those occurring to CVCs under analogous conditions (Neville 1970; Taliercio and Gobbi 1997).

4.5. Poisson Ratio

Figures 9(a) to 9(c) show the long-term Poisson's ratio evolution with time of some specimens from mixes 1, 3 and 4, respectively. The long-term Poisson's ratio is calculated as the ratio between the transverse strain and the longitudinal strain recorded at a given time from the initial loading. As already reported in previous studies (Mazzotti *et al*. 2007), the transverse creep strain rate is

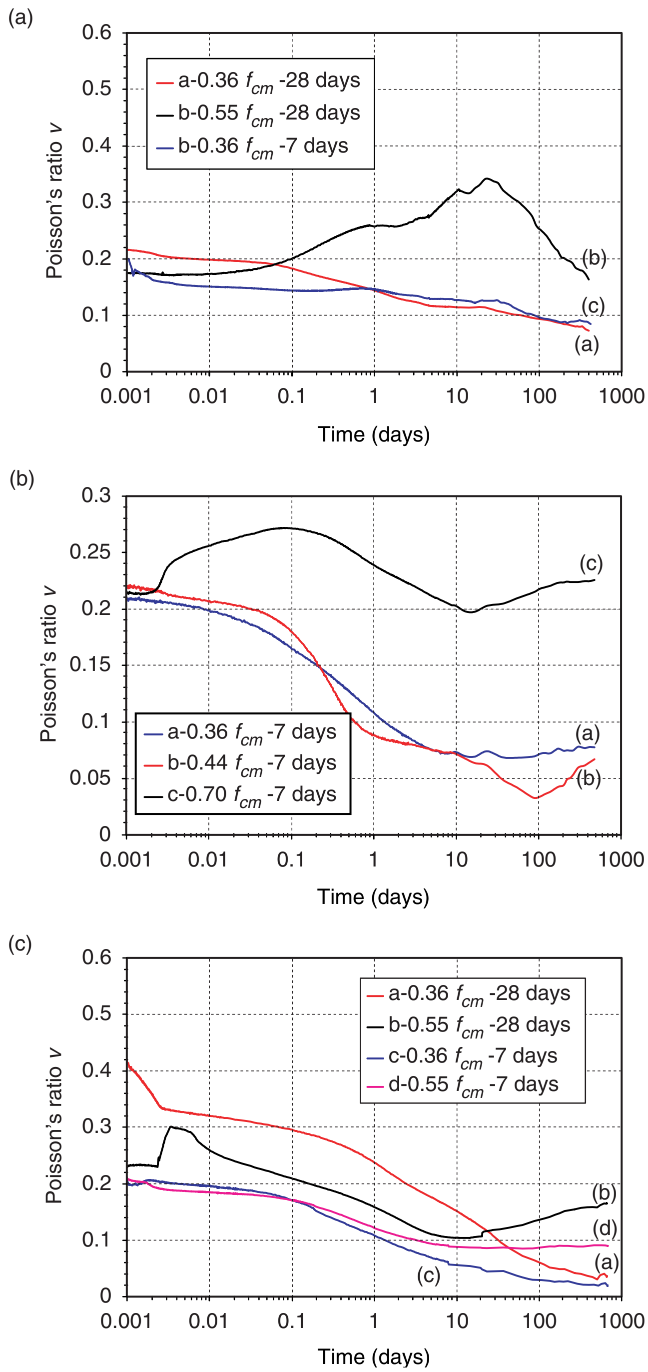


Figure 9. Poisson's ratio evolution with time of specimens from mixes: (a) 1; (b) 3; (c) 4 loaded at different stress levels

much smaller with respect to the longitudinal counterpart, and the Poisson's ratio tends to decrease with time. In more details, a regular decrease of the Poisson's ratio can be observed at medium stress level for all the mixes, probably due to the already mentioned compaction phenomenon; on the contrary, for high stress levels, the initial Poisson's ratio reduction during the first few hours/days (depending on the mix) is followed by an appreciable delayed increase, as a consequence of the transverse micro-cracks generated at this level of the applied stress. This phenomenon is particularly significant for the mix 3 loaded at high stress level (0.7 f_{cm}), see Figure 9(b).

5. COMPARISON WITH SHRINKAGE/CREEP PREDICTION MODELS

The experimental results concerning the total shrinkage (drying + autogenous) strains of the specimens tested have been compared with the values predicted by both the MC90 and the ACI 209 (ACI Committee 209 1992) models in Figures 10(a), 10(b), respectively. These models were originally calibrated using experimental results on CVCs. The comparison is made to verify if they can also be used to predict the delayed strains of SCCs. The shrinkage strain values at 1, 3, 10, 30, 100, 300 days and at the end of the tests have been reported. In the two models considered, not described here for brevity, the shrinkage depends on the environmental conditions, the geometry of the specimen, the age of the concrete at demoulding and the compressive strength.

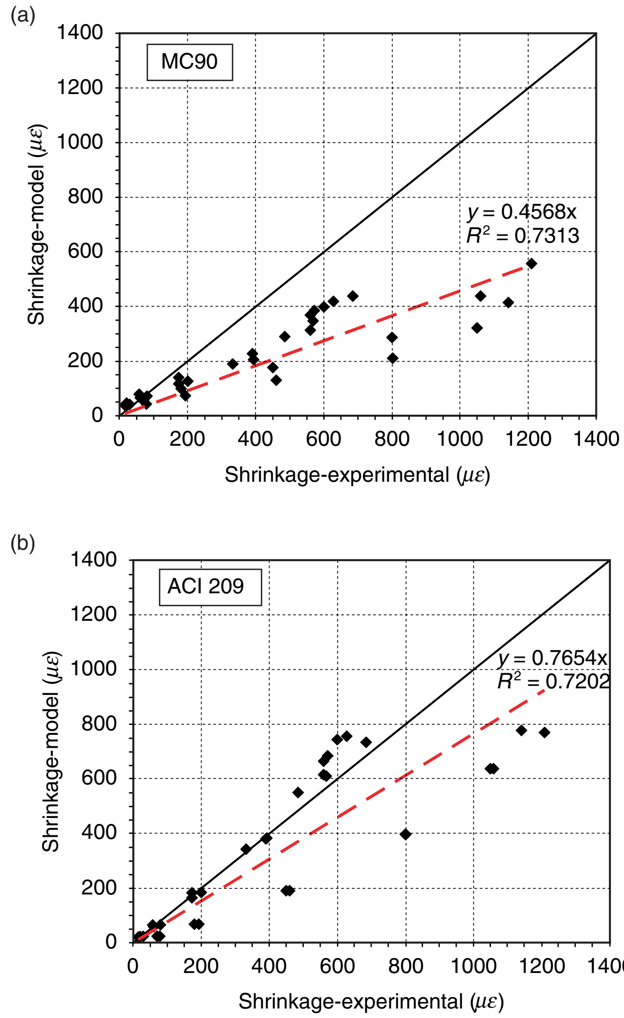


Figure 10. Drying shrinkage: comparison with (a) MC90; and (b) ACI 209 provisions

Only the ACI model includes also the dependence from the workability, the fine aggregates and cement content. According to Figure 10(a), the MC90 strongly underestimates the shrinkage strains, especially for long ages; in previous works (Mazzotti *et al*. 2005), it has been shown that not only the total shrinkage is underestimated, but also the rate of increase with time is poorly described. The ACI 209 predictive model, although underestimating the experimental results too, performs better, showing a measured-to-predicted mean value of 0.76 *vs* 0.45 of the MC90. A remarkable scattering of the predicted-to-measured results is observed for both models, with a coefficient of correlation R^2 of about 0.72. Since the correlation coefficient of the ACI 209 model is only slightly smaller, the proposed dependence of the shrinkage from the mix parameters, considered by the ACI model, seems to be not so effective or to require a more specific calibration, at least for these mixes of self-compacting concrete. It has to be stressed that SCCs are characterised by some mix parameters like *w*/*b*, *amount of fines*, etc… not included in any model thus increasing the scattering, especially with the considered mixes where compositions are widely varied.

Figures 11(a) to 11(c) show the comparison between the experimental creep strains and the creep strains predicted by the MC90, the ACI 209 and the GL2000 (Gardner and Lockman 2001) models, respectively. All the models depend on a series of parameters like the environmental conditions, the geometry of the specimen and the age at loading. The MC90 creep model includes also the dependence from the compressive strength while the ACI model only includes the dependence from the workability, the fine aggregates and the cement content. According to the results reported in Figures 11(a) to 11(c), all the models strongly underestimate the creep strains for both the considered ages at loading (7 and 28 days), with mean predicted-to-measured values between 0.45–0.52. The CEB-FIP MC90 and the GL2000 models perform slightly better than the ACI 209 model. On the contrary, the latter exhibits the smaller scattering of the results with a coefficient of correlation $R^2 = 0.81$ *vs* 0.72 and 0.52 of the MC90 and GL2000 models, respectively; the comparison suggests that the expressions included in the ACI model, taking the effects of some mix parameters into account, are more effective, but they require a specific calibration for SCCs.

The proposed comparisons, both in terms of shrinkage and creep, provided for scattering of results similar to that which can be found considering databases of creep and shrinkage of CVCs and actual predicting models. In this perspective, these models show similar performances with both types of concretes.

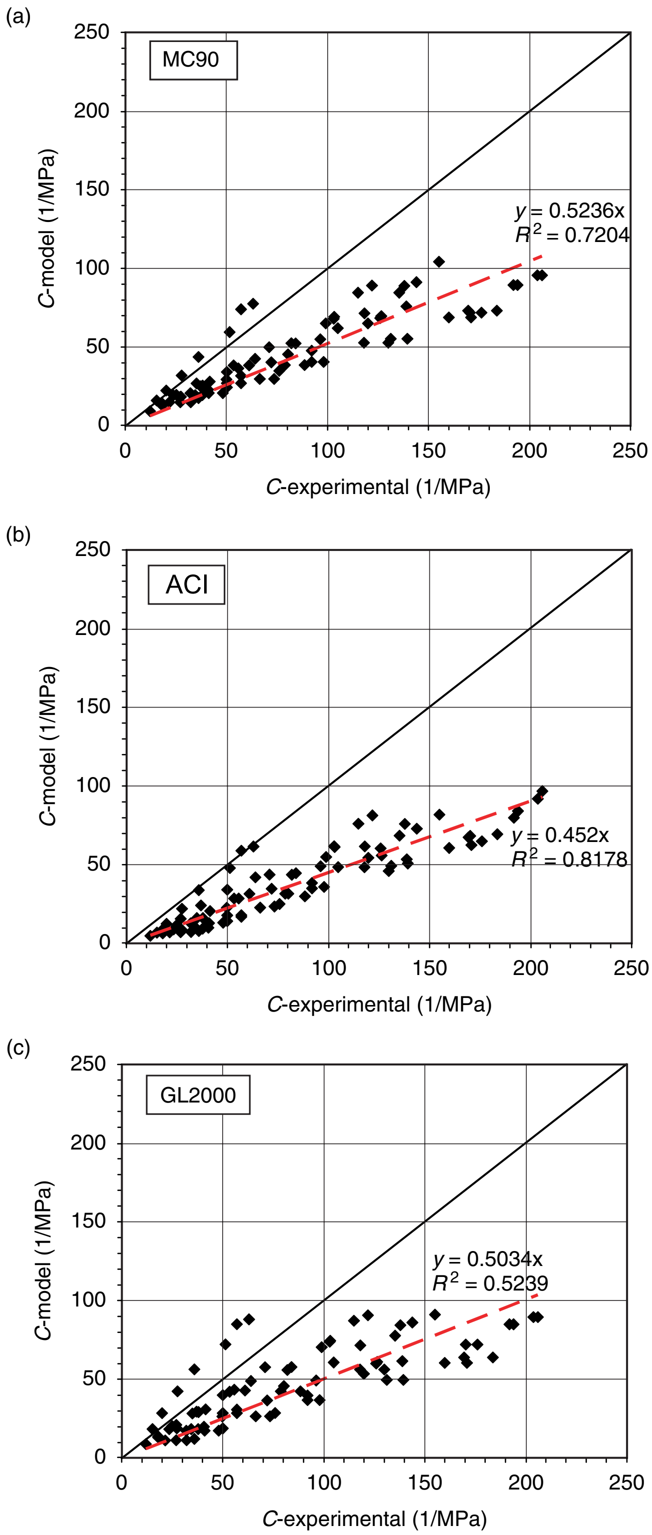


Figure 11. Specific creep C: comparison of the experimental data with (a) MC90; (b) ACI 209; and (c) GL2000 models

6. CONCLUSIONS

The results of a set of experimental tests on the long-term behaviour of the self-compacting concrete have been presented. All the mixes share the same raw materials but have different compressive strengths (the main parameter adopted in European standards to identify the concrete class, although not exhaustive of the mix properties). Finally, the experimental data have been also compared with the predictions obtained from some International Guidelines, and recognised models. Based on the experimental findings and the numerical comparisons, some remarks can be drawn:

(1) The evolution with time of the compressive strength of the SCC mixes can be quite correctly described by using the prediction rules suggested for the CVCs.
(2) On the contrary, the evolution with time of the elastic modulus is well predicted by the conventional models only for low-to-medium strength concrete classes; in fact, the increase of strength with respect to the CVC of the SCCc (mainly due to the smaller *w*/*c* ratio and the adoption of reactive filler) is not associated with an analogous increase of the elastic modulus (at least for young concretes), due to the reduced amount of coarse aggregates in SCCs. Nevertheless, when high strength SCCs are considered, the overestimation of the MC90 predictions is usually no more than 15 to 20%.
(3) The drying shrinkage of SCC specimens is systematically greater than those of both the reference CVC and the code provisions, so confirming previous results in the literature (Loser and Leemann 2009; Roziere *et al*. 2007).
(4) Similarly, the creep strain of the SCC mixes 1–4 are always greater than those of the CVC (mix 6), due to a larger paste volume. More generally, from the experimental tests a dependence of the creep strain from the paste volume and the relative amount of limestone powder replacing the cement can be found, as observed also by other authors (Poppe and De Schutter 2005); the creep strain is greater also if the type of cement is changed from type I to type II with limestone powder addition (II AL). Moreover, the increase of the amount of water, also maintaining the *w*/*p* ratio constant, leads very often to an increase of the creep strain. The dependence of the creep strain from many of these parameters, in the author's opinion, can be captured also by considering the different strength evolution with time of the concretes.
(5) The creep tests have also shown that the conventional stress limit of validity of the linear viscoelasticity theory can be still applied to the SCCs, and that a moderate level of long-term compression enhances the aging of the SCC, providing for a higher residual strength with respect to the unloaded material. This mechanical aspect goes also under the name of "adaptation" (Bazant and Kim 1979).
(6) Finally, the experimental data, both in terms of shrinkage and creep, are appreciably underestimated by International Guidelines and Codes models, originally calibrated by using data from CVCs. Nevertheless, the scattering of results is in a similar range (large), suggesting that more than a new calibration of the involved parameters a more effective inclusion of mix parameters into the models could lead to better results.

ACKNOWLEDGEMENTS

The authors would like to thank SAPABA and BASF for providing the materials for tests. The financial supports of (italian) MIUR (PRIN 2006 Grant: "Structural application of self compacting concrete") is gratefully acknowledged.

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