ABSTRACT: In the present paper, the results of an experimental campaign concerning the long-term behavior of hardened self-compacting concrete are presented. Five mixes of self-compacting concrete and one mix of conventional vibrated concrete have been employed, with different compressive strength. Strength levels have been selected to cover the range of application from cast-in-place to prestressed structures. For each mix, shrinkage and creep tests at two different ages at loading (7 and 28 days) have been performed for a period of about one year. Finally, experimental data both in terms of shrinkage and creep are compared with international code provisions. An apparent underestimation has been observed in all cases but MC2010 in predicting SCC creep behavior, where an over-prediction has been obtained. In general, the introduction inside models of the dependency from specific mix parameters seems to be advisable when considering SCCs.

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 according to very different methodologies, amount of fillers or chemical admixtures (Heirman et al. 2008). 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 particular, due to the limited number of studies (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) only recently the role played by the different components started to be partially clarified. It is 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).

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 the present paper, some results of the experimental campaign concerning the long-term properties of the hardened SCC are presented. 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 C30/37 to C55/67. For each mix, shrinkage and creep tests have been performed for a period of time of about one year (for further details, see Mazzotti et al. 2008). As for the creep tests, two different ages at loading (7 and 28 days) have been considered and a sustained stress levels of about 35% of the compressive strength at the age of loading.

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 CONCRETE MIXES CONSIDERED

In order to compare the long-term 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 Figure 1a, whereas the water/cement (w/c) and water/powder (w/p) ratios, the flow cone and the compressive strength are reported in Figure 1b; for the CVC mix, the classical slump measure is reported.

<table>
<thead>
<tr>
<th>Comp.</th>
<th>Type</th>
<th>Unit</th>
<th>Mix 1</th>
<th>Mix 2</th>
<th>Mix 3</th>
<th>Mix 4</th>
<th>Mix 5</th>
<th>Mix 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>32.5 II AL</td>
<td>kg/m³</td>
<td>355</td>
<td>360</td>
<td>-</td>
<td>-</td>
<td>410</td>
<td></td>
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<tr>
<td>Cement</td>
<td>42.5 II AL</td>
<td>kg/m³</td>
<td>-</td>
<td>-</td>
<td>440</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Cement</td>
<td>52.5 I N</td>
<td>kg/m³</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>440</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Cement</td>
<td>52.5 I R</td>
<td>kg/m³</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>Filler</td>
<td></td>
<td>kg/m³</td>
<td>199</td>
<td>173</td>
<td>110</td>
<td>110</td>
<td>100</td>
<td></td>
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<tr>
<td>Sand 0-4 mm</td>
<td></td>
<td>kg/m³</td>
<td>968</td>
<td>863</td>
<td>826</td>
<td>826</td>
<td>675</td>
<td></td>
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<tr>
<td>C. sand 8-12 mm</td>
<td></td>
<td>kg/m³</td>
<td>470</td>
<td>550</td>
<td>520</td>
<td>520</td>
<td>340</td>
<td></td>
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<tr>
<td>Gravel 12-25 mm</td>
<td></td>
<td>kg/m³</td>
<td>182</td>
<td>181</td>
<td>240</td>
<td>240</td>
<td>800</td>
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<tr>
<td>HRWRA</td>
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<td>l/m³</td>
<td>6.30</td>
<td>8.70</td>
<td>6.75</td>
<td>6.75</td>
<td>4.4</td>
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<tr>
<td>VMA</td>
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<td>l/m³</td>
<td>0.70</td>
<td>0.90</td>
<td>0.75</td>
<td>0.75</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td></td>
<td>l/m³</td>
<td>173</td>
<td>205</td>
<td>204</td>
<td>209</td>
<td>180</td>
<td></td>
</tr>
</tbody>
</table>

Figure 1 - (a) Mix composition of SCC and CVC mixes and (b) physical and mechanical properties of considered mixes.

The SCCs have been cast with different types of cement and amount of super plasticizer and VMA (coupled together) and they have slightly different w/p ratio; 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.
3 EXPERIMENTAL SET-UP AND INSTRUMENTATION

The delayed deformations of the SCC mixes have been investigated by performing tests on 122×250 mm (φ×h) cylinders. For all the mixes but mix 5, four cylinders have been used for creep tests at two different ages at loading and three cylinders for the shrinkage tests. 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. For all the specimens, a stress level of about 35% of the compression strength at the loading time $f_{c0}$ has been adopted.

The creep strains 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. The specimens subjected to the shrinkage tests have been instrumented similarly; the drying shrinkage 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 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 2. The mixes 3 and 4 show remarkably higher values of the total shrinkage with respect to mixes 1 and 2; this is probably due to the type of cement adopted (42.5 and 52.5 instead of 32.5) and to the relatively greater paste volume. The shrinkage strain of mix 2 is smaller with respect to the other mixes 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. 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).

![Figure 2 - Total shrinkage strains of all mixes.](image-url)
RESULTS FROM CREEP TESTS

For all the mixes loaded at 7-day age from casting, the specific creep functions $C = (\varepsilon_v / \sigma)$ ($\varepsilon_v$ and $\sigma$ being the viscous strain and the applied stress) are given in Figure 3a. In Figure 1b, 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 (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 & Kim 1979) which reduced the delayed creep strains.

![Figure 3a](image1.png)

![Figure 3b](image2.png)

Figure 3 - Specific creep of all mixes at (a) low and (b) high stress levels for 7-day age at loading.

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The different creep behavior of the four concretes can be explained by considering the different mix-designs (Table 1). The two mixes 1 and 4 have a similar paste volume (about 185 l/m³) and mix 1 has an higher amount of limestone filler (which should increase the creep according to Poppe and De Schutter 2005); nevertheless, the mix 4 has an higher amount of water and a greater creep strain; this last consideration suggest that the amount of water has a far more greater influence on the creep behavior respect to others mix parameters. Furthermore, comparing the creep behavior 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 volume of limestone filler 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), 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 and the fines is not leading to a more pronounced viscous behavior (mix 1 vs mix 6) (Seng and Shima 2005).

The long-term behavior of the SCC specimens loaded at an age of 28 days is reported in Figure 3b. As expected, the specific creep of the mixes 1 to 4, after about one year of loading, is 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 viscous behavior. The reduced viscosity 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 a smaller paste volume (18 l/m³ less) and a smaller w/c ratio.

6 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 the MC90, MC2010 (fib 2010) and the ACI 209 (ACI Committee 209 1992) models in Figures 4a, b, respectively. These models were originally calibrated using experimental results on CVCs. The comparison is made to verify if they can 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 three 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. Only the ACI model includes also the dependence from the workability, the fine aggregates and cement content. According to Figure 4a, 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. In the last version of the MC (2010), the shrinkage model has been modified and re-calibrated obtaining larger predicted values but still smaller than experimental values. 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 and vs 0.72 of the MC2010. A remarkable scattering of the predicted-to-measured results is observed for all models, with a coefficient of correlation $R^2$ of about 0.72 for MC90 and ACI 209 models while MC2010 show the worst performance with $R^2$ of 0.51. Since the correlation coefficient of the ACI 209 model is only slightly smaller than MC90, 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. Furthermore, the improvements of MC2010 seem to be not so
effective for SCCs (at least for the reduced number of experimental test considered here).

Figures 5a-c show the comparison between the experimental specific creep data and the same data 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, 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. Finally, also predictions by the very recent MC2010 have been compared with experimental data (Figure 5d); from a qualitatively view point, this creep model is almost identical to the one from MC90. Only some correction factors depending from the concrete strength have been added. Quantitatively, some coefficients have been re-calibrated. Comparison shows that the model overpredicts the experimental results while keeping a scattering ($R^2$) similar to the previous MC90. Nevertheless, the mean predicted-to-measured values (1.33) is better respect to all the previous considered models.

Figure 5 - Specific creep C – Comparison of the experimental data with (a) MC90, (b) ACI 209, (c) GL2000 and (d) MC2010 models.

7 CONCLUSIONS

The results of a set of experimental tests on the long-term behavior of the self-compacting concrete have been presented. Five SCC mixes and one CVC mix have been tested and the corresponding results compared. 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 Standard (i.e., MC90, MC2010 and ACI) and recognized models (GL2000). Based on the experimental findings and the numerical comparisons, some remarks can be drawn:

1. 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). The greater values of the shrinkage of mixes 3 and 4 are mainly due to the use of 42.5 and 52.5 type I cements and to the slightly greater paste volume.

2. Similarly, the creep strain of the SCC mixes 1-4 are always greater than those of the CVC (mix 6), due to a paste volume about 50 l/m³ greater. 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.

3. Finally, the experimental data, both in terms of shrinkage and creep, are significantly different from those predicted by International Guidelines and Codes, originally calibrated by using data from CVCs. Hence, the study confirms that not only a new calibration of the parameters is needed to predict the delayed strains of SCCs but, probably, also the time evolution laws should be modified. Only the new MC 2010 over-predicts the experimental finding because of a new calibration and not to the introduction of new dependencies.

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REFERENCES


