# Long-term behavior of self-compacting and normal vibrated concrete: Experiments and code predictions

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The paper presents an experimental investigation that compares the long-term behavior (creep and shrinkage up to 680 days) of a Normal Vibrated Concrete (NVC) and a Self Compacting Concrete (SCC), with the latter being obtained by a slight change in mix-design (mainly an increase of the fly ash content to achieve self-compactability). It is shown that SCC exhibits higher shrinkage but the creep behavior is almost similar. As observed in other researches, this investigation confirms the influence of some param-eters (i.e. cement content, water/cement ratio, type of filler) on the long-term behavior.

The tests were conducted for a very long period (680 days) with respect to data usually available in lit-erature and, for this reason, it was possible to measure the asymptotic values and compare them with the code predictions. This comparison showed the importance of the modulus of elasticity (experimentally detected and different from the code based value) to predict the service behavior of a reinforced concrete element.

Most codes seem to underestimate the creep behavior of the SCC concrete mix, thus they cannot be applied directly and the MC2010 suggestion to consider higher (10–20%) long-term deformation for SCC powder type concrete seems to be reasonable, as well as the suggestion to perform tests on the mate-rial for structures sensitive to variations in creep/shrinkage (i.e. redundant structures).

**Keywords**: Self-compacting concrete Creep, Shrinkage, Experimental investigation

**Highlights**

- SCC was achieved with a slight change in the mix-design of NVC (mainly by changing the amount of fly ash).
- SCC exhibited higher shrinkage, while the total creep deformation was similar.
- NVC and SCC specimens subjected to constant load seem to reach an asymptotic value at about 500 and 550 days, respectively.
- Codes seem to underestimate the experimentally observed deformation.
- By inserting in the code formula the experimental modulus of elasticity the code predictions significantly improve.

## 1. Introduction

In the last two decades the applications of Self Consolidating Concrete (SCC) have become very popular due to its peculiar characteristics. The basic feature consists in its ability to be poured into formworks without using vibration [1,2], with evident benefits in precast plant as well as in building systems with complex structural scheme and dense reinforcements.

To achieve these properties, the proportion of the mix constituents differs from Normal Vibrated Concrete (NVC). Higher volume of fines, addition of chemical admixture, limited amount of coarse aggregate and reduced size of the aggregate are basic requirements to be successful in manufacturing SCC [2,3].

These differences in the mix-design with respect to NVC cause a completely different internal structure, thus many researchers studied not only the fresh state, but even the hardened state mechanical properties (i.e. compressive strength, bond strength, shear strength…) [4–9]. The long-term behavior has been investigated as well, but most of the studies focused on shrinkage only, considering different aspects such as the paste volume, the water

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content, the mineral admixtures, the coarse aggregate volume and grading *and the type of testing* [10–17]. Some researches paid particular attention on the autogenous shrinkage which appears to be affected by several parameters such as the water/cement ratio and the fines/cement ratio [10–15]. Oliviera et al. [13] showed that with a proper balance between expansive and shrinkage reducing admixture (SRA) it was possible to design a mix with a prescribed shrinkage. In [15] it is shown that Eurocode 2 [18] underestimates the autogenous shrinkage while total shrinkage is generally overestimated.

Nevertheless, due to the timing in testing, studies on creep are rather limited and some contradictory results can be found in literature [19–25].

Creep behavior is strongly affected by several parameters (such as curing conditions, age of loading, cement content, aggregate type and size, water cement ratio, relation of coarse to fine aggregates as well as fineness – blaine – and content of ultrafines which affect the paste volume) and, for this reason, in the available research investigations it is not easy to separate the single effects.

Maia et al. [19] focused on the effect of the age of loading and of the stress level on the total deformation. Even though the considered concrete was not common (24 h compressive strength higher than 60 MPa), the authors' conclusions highlight that Eurocode 2 [18] only in some cases well predicts the total deformation, and thus the authors suggest to measure deformation at least for one year.

The serviceability limit state and the overall behavior of a reinforced or prestressed concrete structure strongly depends on the long-term properties, which can significantly affect the overall response, in terms of excessive deformations, displacements and cracks, and cause several damages [26–32]. For instance, even in simple cases such as precast composite concrete-glass panels [32], long term deformations caused cracks which affected the aesthetic and the durability of the building, with relevant economic consequences. Thus, designers need to be confident of reliable code provisions that allow to evaluate the long-term strains. Nonetheless studies on creep for SCC concrete are rather few, and reviews on this topic [33–35] suggest the need of additional research, even if in the meantime they propose some general conclusions.

It seems that the paste volume strongly affects the shrinkage behavior [16], while the effect on creep is less pronounced. At the same time, creep is strongly affected by the binder type and content [21,24]. These findings were confirmed by Arezoumandi et al. [20], who compared two concretes (NVC and SCC) with the same composition with self-compacting ability achieved through a Viscosity Modifying Agent. They found higher compressive strength (of about 22%) of SCC while creep and shrinkage behavior of the two concretes were very similar. In addition, they found in their case study that the creep coefficient was overestimated by both ACI209 [36] and CEB-FIP Model Code 2010 [37], while shrinkage is well predicted by ACI209 [36] and underestimated by CEB-FIP Model 2010 [37]. On the other hand, Long [24] found that CEB-FIB MC90 [38] seems to well predict creep values with respect to ACI209 [36].

The code provisions are empirically based on a wide database of experimental NVC results, thus they could not be suitable for SCC.

In this paper, the comparison between shrinkage and creep behavior (specimens loaded for 680 days) of an ordinary (NVC) and a self-consolidating concrete (SCC) is presented. Sealed and unsealed specimens were considered. The mix-designs of the two concretes were similar, since they were conceived to achieve self-compacting ability with minimum changes in powder content. The maximum aggregate size was 22 mm, and fly ash was used as filler.

The obtained results are compared with other researches available in literature, to find similarity or discrepancy in the behavior and identify the most important parameters affecting the long term behavior of a concrete component. Although the shrinkage has been studied by several authors, the creep behavior, to date, has been investigated in few researches and for a limited time (usually less than one year). The tests last for 680 days and allow to identify the time when an almost asymptotic value of deformation was reached. Strength and Young's modulus were determined and discussed as well. Finally, a comparison with some of the most common code provisions (EC2 [18], CEB-FIB MC90 [38], CEB-FIP Model 2010 [37], ACI209 [36]) is presented, to check their capacity to predict the long term behavior of SCC concrete.

## 2. Experimental program

### 2.1. Materials

The experimental tests were performed on specimens made with SCC and NVC concrete designed for a cubic compressive strength ($f_{cc}$) of about 37 MPa (C30/37). Mix-components of the cement-based materials used for this investigation are summarized as follows: a Portland cement CEM II-A/LL 42.5R (340 kg/m$^3$ and 370 kg/m$^3$ for NVC and SCC, respectively); fly ash (6% and 22% cement content by weight for NVC and SCC, respectively); an acrylic superplasticizer (1.05% and 1.1% cement content by weight for NVC and SCC, respectively); a maximum aggregate size of 22 mm. NVC and SCC had an aggregate/binder ratio of 5.2 and 4.0, a water/cement ratio of 0.49 and 0.47 and a water/binder ratio of 0.46 and 0.39, respectively.

Workability was evaluated with slump for NVC (245 mm) and slump-flow tests for SCC (690 mm). The mechanical characteristics of the two concretes (NVC and SCC, respectively) can be summarized as follows: average compressive cubic (side 150 mm) strengths ($f_{cc}$) at 7 days 34.1 MPa and 35 MPa, increasing to 44.7 MPa and 45.5 MPa at 28 days (evaluated according to EN12390-3 [39]), while the elastic modulus (cylinder with diameter of 150 mm, height 300 mm) at 28 days were 27.2 GPa and 26.7 GPa, respectively (evaluated according to EN12390-13 [40]).

### 2.2. Test specimens

Sixteen cylindrical specimens (8 SCC and 8 NVC) were casted (diameter 150 mm, height 400 mm).

Four specimens of each mix were sealed with a self-adhesive plastic sheet to prevent any moisture loss due to drying.

For each type of concrete, two sealed and two unsealed specimens were subjected to constant load (creep tests), while the other specimens (two sealed and two unsealed) were left unloaded to measure shrinkage. Thus, two twin specimens were considered for each type of test.

Each specimen had a proper code as shown in Table 1: Concrete type (SCC or NVC), measure (S- shrinkage or C-creep), curing conditions (S-sealed, F-free), specimen number (1 or 2).

### 2.3. Test procedure

The specimens were demolded after 24 h. The specimens identified by code XXX-X-S-X were wrapped with a self-adhesive

**Table 1**
Specimens' code.

| Unloaded and sealed | Unloaded and unsealed | Loaded and sealed | Loaded and unsealed |
|---|---|---|---|
| SCC-S-S-1 | SCC-S-F-1 | SCC-C-S-1 | SCC-C-F-1 |
| SCC-S-S-2 | SCC-S-F-2 | SCC-C-S-2 | SCC-C-F-2 |
| NVC-S-S-1 | NVC-S-F-1 | NVC-C-S-1 | NVC-C-F-1 |
| NVC-S-S-2 | NVC-S-F-2 | NVC-C-S-2 | NVC-C-F-2 |

**Fig. 1.** Specimen with markers.

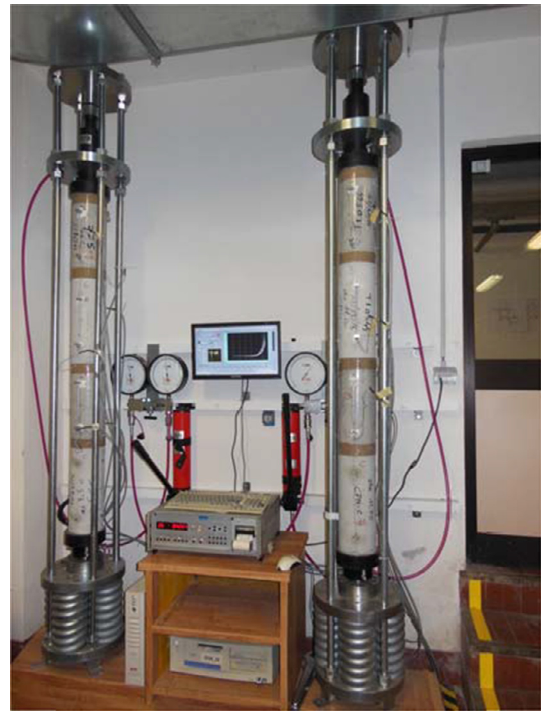

**Fig. 2.** Testing frames for creep tests.

plastic sheet while specimens identified by code XXX-X-F-X were left unsealed.

On the surface of all specimens, 2 pairs of pre-drilled brass discs were glued in two opposite positions along the cylinder's generator at a distance of 250 mm as shown in Fig. 1 to allow the use of a Demec gauge (Huggenberger deformeter-resolution 0.001 mm).

All specimens were cured in a climatic chamber at controlled temperature (20 ± 2 °C) and humidity (50 ± 5%).

### 2.4. Shrinkage test

Shrinkage was evaluated on unloaded specimens both sealed (XXX-S-S-X) and unsealed (XXX-S-F-X) by measuring the displacement between the two pre-drilled brass discs over time by means of the Demec gauge.

The measurements were performed every 24 h in the first 10 days, then weekly and monthly.

### 2.5. Creep test

The specimens were loaded at 28 days in two frames designed to maintain a constant sustained load (Fig. 2). Four specimens (two sealed and two free) were inserted in each frame according to ASTM 512 [41]. The applied stress was equal to 14.7 MPa to fall in the linear creep range suggested by ASTM 512 [41] (up to 40% of the cylindrical 28 days strength) and by the draft of the European standard prEN CEN/TC104 [42] (1/3 of the cylindrical 28 days strength).

Each frame was equipped with a load cell (300 kN, class I), the displacements were measured between the two pre-drilled brass discs by means of the Demec gauge, and on each specimen two additional LVDT transducers HBM W1ELA/0 (±1 mm, gauge length 200 mm) were placed to measure the displacements continuously.

The loads and the displacements were acquired with a data acquisition system HBM UPM60.

## 3. Experimental results

### 3.1. Mechanical properties

At the end of the tests (680 days) the shrinkage specimens were tested to evaluate the elastic modulus and the compressive strength. The elastic modulus evaluated on unsealed specimens were 27.4 GPa for SCC and 29.6 GPa for NVC specimens respectively. Thus it seems that the SCC modulus was almost constant over time (increase of about 2%) while for NVC there was a slightly larger increase (8%). The cylindrical compressive strengths are shown in Fig. 3, where it is noticeable that the increase of strength is similar for the two concretes, and that in sealed conditions (S) the strength considerably increases with respect to free conditions (increase of about 31% for both concretes).

As discussed in Section 2.1 the cubic compressive strength at 28 days were 45.5 MPa and 44.7 MPa for SCC and NVC respectively. Thus the not sealed 680 days-cylindrical/28 days-cubic compressive strength ratio was about 0.83 (SCC) and 0.86 (NVC). It is worth noting that the cylindrical strength was evaluated after about two

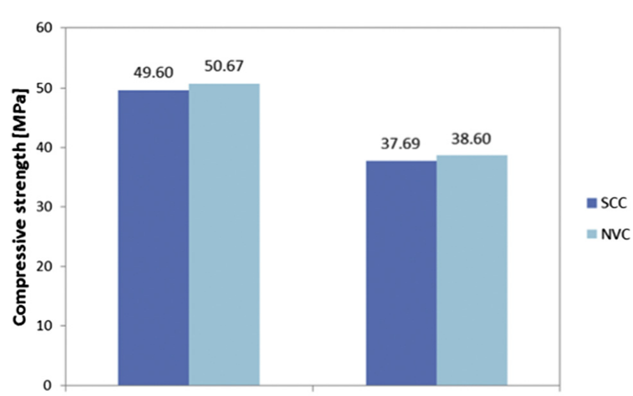


**Fig. 3.** Compressive strength at 680 days.

years when, due to the pozzolanic effect especially of fly ash, the compressive strength was expected to increase beyond the 28 days strength. This suggests that the ratio between cylindrical/cubic compressive strength could be lower and as a consequence, in practical application the SCC cylindrical strength has to be evaluated to check whether the typical value assumed in some codes 0.83 for NVC is still valid or not.

### 3.2. Shrinkage tests

Fig. 4 shows the shrinkage of each specimen (a) (as average value of the two measurements performed on the opposite side of each specimen) and the average of the measurements on two twin specimens (b), measured over time for sealed (S) and unsealed specimens (F).

It can be noted that the behavior of the twin specimens was similar with differences between measurements taken on twin specimens always around ±7–8% except of some single points (of about 15%).

The unsealed specimens measurements allow to evaluate the total shrinkage $\varepsilon_{st}(t,t_s)$ which is the sum of the drying $\varepsilon_{sd}(t,t_s)$ and of the autogenous shrinkage $\varepsilon_{sa}(t,t_s)$ (measured on sealed specimens).

$$\varepsilon_{st}(t,t_s) = \varepsilon_{sd}(t,t_s) + \varepsilon_{sa}(t,t_s) \tag{1}$$

It can be noted that SCC exhibits higher shrinkage strains in both sealed and unsealed conditions.

It turned also out that sealed specimens exhibit very high autogenous shrinkage strains. This result seems to be unusual since, for the considered cement content and water/cement ratio the autogenous shrinkage should be limited, and the slightly higher cement content seems not to justify these results. However, both concretes contained fly ash, which may affect in different way the autogenous shrinkage as shown by several researchers [10,12,15,43–45]. Those studies investigated the effect of different mineral additions on the autogenous shrinkage and highlighted that the shrinkage behavior may be affected by the degree of hydration of fly ash and by the amount of fine pores.

Alrifai et al. [12] studied autogenous shrinkage in mixes with limestone filler and found that it increases with decreasing water/cement ratio or decreasing limestone filler/cement ratio. Their main conclusions was that a decrease in porosity is accompanied by an increase in autogenous shrinkage. Similar results were found by other authors [15]. Beside the obtained results (with very low autogenous shrinkage) Roziere et al. [10] highlighted that different testing procedures could lead to different results, and this conclusion could be an additional explanation of some contradictory results available in literature.

However, these aspects were not considered in the present paper because out of the scope of the study.

### 3.3. Creep tests

Fig. 5 shows the total strain $\varepsilon_{ct}(t,t_0)$ of loaded specimens over time (loaded at time $t_0$ equal to 28 days) for sealed and unsealed specimens. In particular, Fig. 5(a) visualizes one measurement for each specimen (computed as average of the two measurement taken on the opposite sides of each specimen), while in Fig. 5(b) it is reported the average of the measurements on two twin specimens. The continuous lines and dots represent respectively the measures acquired continuously (LVDT) and manually (Huggenberger).

It can be noted that the continuous measurements performed on the twin sealed specimens are very similar with almost no difference, while those related to the twin unsealed specimens present some scatter: around ±5% and ±7% for SCC and NVC specimens, respectively. In terms of discrete measurements, the difference between measurements taken on twin specimens is always around ±5%.

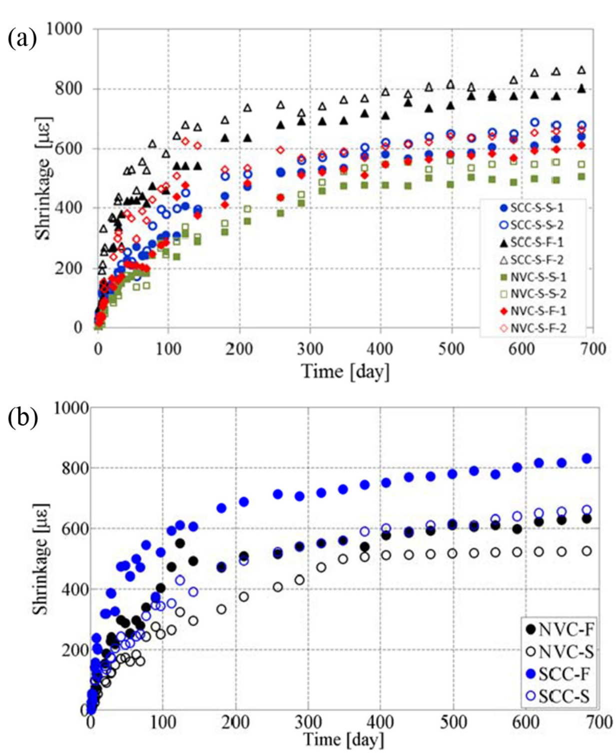


Fig. 4. Shrinkage tests results (a) single specimens (b) average value.

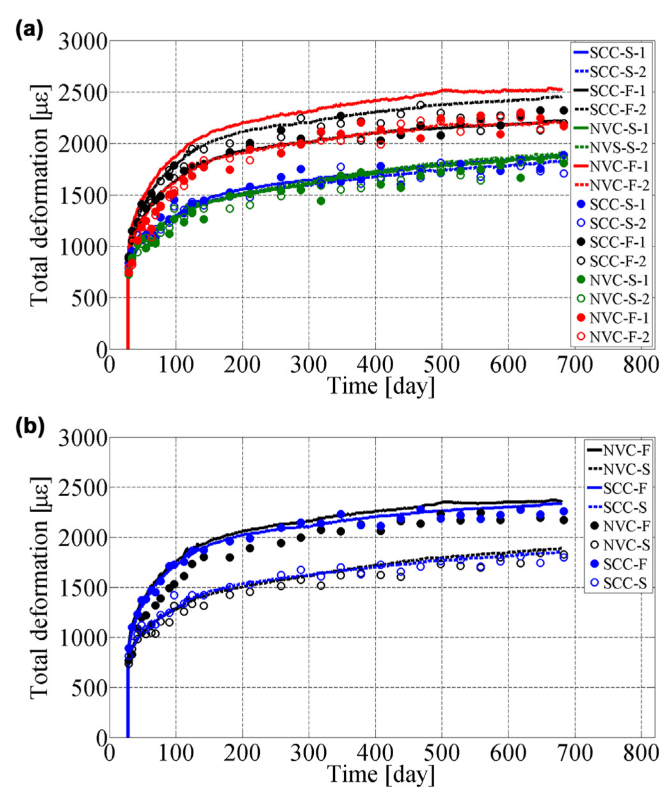


Fig. 5. Creep tests results – Total deformation (dots – discrete measurements, continuous line – continuous measurements). (a) single specimen (b) average value.

The total deformation $\varepsilon_{ct}(t,t_0)$ is the sum of the stress dependent strain $\varepsilon_{c\sigma}(t,t_0)$ and the stress independent strain $\varepsilon_{cn}(t, t_0)$ which can be assumed as the total shrinkage strain $\varepsilon_{st}(t,t_s)$.

$$\varepsilon_{ct}(t,t_0) = \varepsilon_{c\sigma}(t,t_0) + \varepsilon_{st}(t,t_s) \tag{2}$$

The stress dependent strain is the sum of the elastic strain $\varepsilon_{ce}(t_0)$ due to the applied load and of the creep strain $\varepsilon_{cc}(t,t_0)$:

$$\varepsilon_{ct}(t,t_0) = \varepsilon_{ce}(t_0) + \varepsilon_{cc}(t,t_0) + \varepsilon_{st}(t,t_s) \tag{3}$$

The experimental results show again that unsealed specimens (F) exhibit larger strains, with differences between sealed/unsealed of about 20%.

Nevertheless, the difference between NVC and SCC total strains of loaded specimens is almost negligible.

To evaluate the creep effect, the creep coefficient $\varphi$ defined as the ratio between the creep strain and the elastic strain can be evaluated (Fig. 6) as:

$$\varphi(t,t_0) = \frac{\varepsilon_{cc}(t,t_0)}{\varepsilon_{ce}(t_0)} \tag{4}$$

it results:

$$\varepsilon_{cc}(t,t_0) = \varepsilon_{ce}(t_0)\varphi(t,t_0) = \frac{\sigma_c(t_0)}{E_{ci}}\varphi(t,t_0) \tag{5}$$

where $\sigma_c(t_0)$ is the applied stress at the time $t_0$ and $E_{ci}$ is the elastic modulus at 28 days.

The creep function $J$ (or creep compliance) was also considered to evaluate the creep effect (Fig. 7).

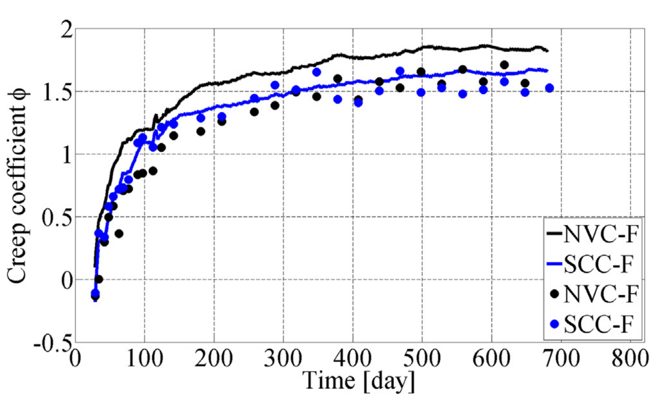


**Fig. 6.** Creep tests results – Creep coefficient (dots – discrete measurements, continuous line – continuous measurements).

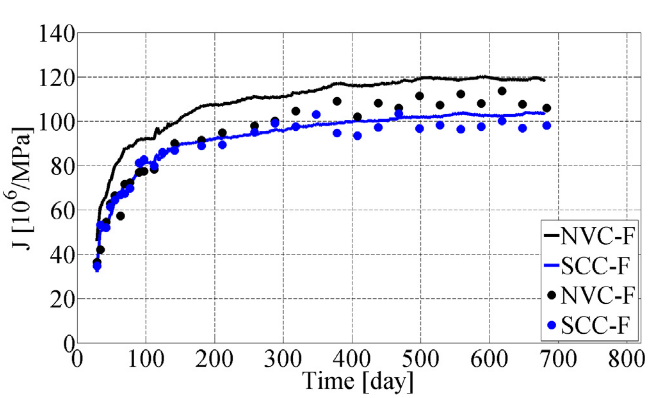


**Fig. 7.** Creep tests results – Creep compliance (dots – discrete measurements, continuous line – continuous measurements).

This coefficient is related to $\varphi(t,t_0)$ by the following equation (where $E_c(t_0)$ is the elastic modulus at the time $t_0$):

$$\varepsilon_{c\sigma}(t,t_0) = \varepsilon_{ce}(t_0) + \varepsilon_{cc}(t,t_0) = \frac{\sigma_c(t_0)}{E_c(t_0)} + \frac{\sigma_c(t_0)}{E_{ci}}\varphi(t,t_0)$$
$$= \sigma_c(t_0)\left(\frac{1}{E_c(t_0)} + \frac{\varphi(t,t_0)}{E_{ci}}\right) = \sigma_c(t_0)J(t,t_0) \tag{6}$$

It follows that:

$$J(t,t_0) = \frac{\varepsilon_{cc}(t,t_0) + \varepsilon_{ce}(t,t_0)}{\sigma(t_0)} = \frac{\varepsilon_{ct}(t,t_0) - \varepsilon_{st}(t,t_0)}{\sigma(t_0)} \tag{7}$$

It can be noted that since the total strains $\varepsilon_{ct}(t,t_0)$ are very similar for the two concretes while the shrinkage strains $\varepsilon_{st}(t,t_0)$ are larger for SCC, the creep coefficient and the creep compliance are higher in NVC.

From Figs. 6 and 7 it emerges also that at about 500 and 550 days NVC and SCC specimens seem to reach an asymptotic value, respectively.

## 4. Discussion

### *4.1. Comparison with other experimental researches*

The long-term behavior of SCC has been investigated by several researchers [10–17,19–25], but most of them focused their attention on shrinkage behavior [10–15] while the studies on creep are rather limited [19–25].

It is well known that the long term behavior of concrete is strongly affected by several parameters such as: curing conditions, age of loading, cement content, aggregate type and size, water cement ratio, relation of coarse to fine aggregates as well as fineness (Blaine) and content of ultrafines which affect the paste volume.

Thus, it is not easy to compare the results of different researches, nevertheless some comments can be drawn (Fig. 8).

Arezoumandi et al. [20] studied the long term behavior by comparing a self-compacting concrete (SCC) with an ordinary concrete (CC) with the same mix (cement CEM I -112 kg/m$^3$, fly ash 112 kg/m$^3$, aggregates 1632 kg/m$^3$) except for a Viscosity Modifying Agent (VMA) added to achieve self-compaction. They noted a very similar long term behavior (in terms of both shrinkage and creep) for both concretes.

The only difference between SCC and CC was an increase of the compressive concrete strength confirmed even by other researchers [46]. The findings contained in [21,24,33,34] confirm that the paste volume and the type of binder have a strong influence on the long term behavior of concrete.

Mazzotti et al. [21] studied the behavior of several mixes obtained by combining VMA (addition between 0.7 and 1 L/m$^3$ depending on the mix) and a filler (limestone ranging from 100 to 200 kg/ m$^3$ depending on the mix), and found much higher shrinkage strain, even if they measured shrinkage starting from 3 days and in less severe curing conditions (RH equal to 60%). Indeed, they used a higher cement content (ranging from 355 to 440 m$^3$ depending on the mix) and a lower cement/binder ratio (between 0.31 and 0.39). The authors supposed that this result is due to the type of cement and to the greater paste volume.

Vieira and Bettencourt [25] found a very limited shrinkage strain, this could be explained because they used a very low amount of cement (205 kg/m$^3$ for SCC and 230 kg/m$^3$ for NC) with a limited amount of fly ash (102 kg/m$^3$ for SCC and 70 kg/m$^3$ for NC), while in SCC they added even limestone filler (256 kg/m$^3$).

Similarly Leeman et al. [22] found a great influence of the type of cement on the shrinkage behavior, with decreasing strain by considering CEM I, CEM I/B-M and CEM III/B, in the meantime

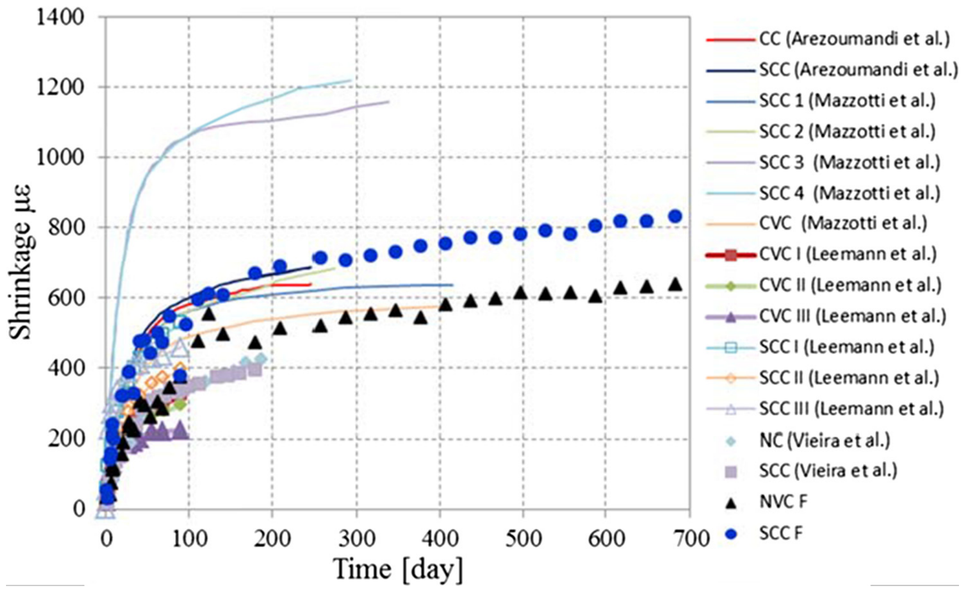


**Fig. 8.** Shrinkage strains: comparison with other authors.

the counterpart SCC of ordinary concrete, characterized by a higher paste volume, exhibited higher deformation.

Both SCC and NVC specimens presented in this investigation show a behavior comparable to many of the considered studies. In particular SCC exhibited shrinkage strains similar to Arezoumandi et al. [20] and to Mazzotti et al. [21] (SCC1 and SCC2). In the case of Arezoumandi et al. [20] this could be explained because many parameters were equivalent (i.e. water/powder ratio of about 0.40, similar maximum aggregate size 19 mm and 22 mm), while in the case of Mazzotti et al. [21] it is not so easy to establish an equivalence, since many parameters were different: the cement was the same only for Mix 3, but with an higher amount (440 kg/m$^3$ for Mix 3 and 340 kg/m$^3$ for SCC) and with different fillers (limestone vs fly ash) although the water/powder ratio was similar (0.37 vs 0.39).

Anyway, it has to be noted that the maximum aggregate size of many of the considered concretes was relatively large for a SCC ([20] 19 mm and [21] 25 mm).

Regarding the NVC it seems that up to three months it has a behavior similar to those observed in the other studies, but then it shows a behavior similar to the conventional vibrated concrete CVC of Mazzotti et al. [21].

The two concretes had comparable aggregate content (1872 vs 1770 kg/m$^3$) with similar distribution between fine and coarse volume (782 vs 751 kg/m$^3$ fine – 1090 vs 1019 kg/m$^3$ coarse). The cement type and content were different in particular NVC used a CEM 42.5R II/A-LL (340 kg/m$^3$) while CVC used a CEM 32.5 II AL (410 kg/m$^3$). Thus it seems that the aggregate amount and grading plays an important role, as found even by other authors [11].

Nevertheless, most of the other concretes were tested for a shorter period and thus, due do the lack of data, additional comments cannot be drawn.

As for creep results, these have been compared with results in literature in terms of creep coefficient and the creep compliance, in order to take into account the different adopted testing parameters, such as age at the time of loading, temperature and relative humidity, specimen size, ratio between compressive strength and applied load.

By comparing the creep compliance (Fig. 9) it can be noted that the SCC1 [21] shows a behavior similar to SCC, as for shrinkage. Nevertheless, the two concretes have a quite different mix-design as well as curing conditions. Only the water/cement ratio was similar, but even the amount and the type of powder differed. Indeed, the amount of limestone filler in SCC1 was higher with respect to the amount of fly ash in SCC concrete. It seems that this confirms the findings of other researchers [34] who concluded that fly ash addition may drastically affect the results in terms of creep deformation.

Even by comparing the creep coefficient (Fig. 10) it can be noted that the concretes (SCC of the present investigation and SCC in Arezoumandi [21]) which exhibited similar shrinkage behavior have an analogous creep coefficient.

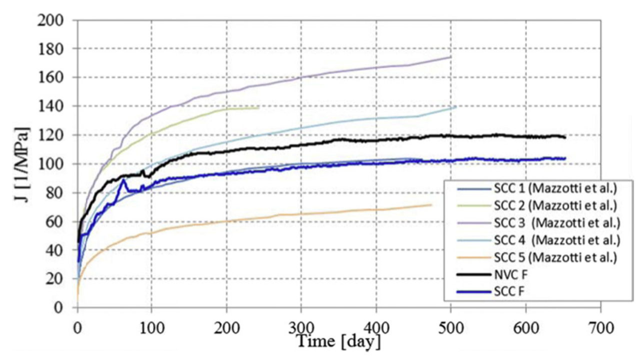


**Fig. 9.** Creep compliance: comparison with other authors.

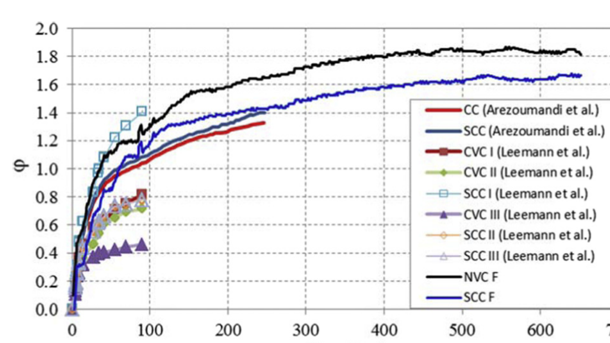


**Fig. 10.** Creep coefficient: comparison with other authors.

In this case, the two mix-designs have some very similar parameters, such as water/cement and water/powder ratio, fly ash filler, and a similar amount of coarse aggregate.

The mixes studied by Leemann et al. show lower creep coefficient except SCC-I which is characterized by a high amount of CEM I (520 $kg/m^3$). Nonetheless the time of testing was limited and thus an asymptotic was not observed.

It has to be noted that SCC5 [21] (Fig. 9) shows a very low creep compliance, this behavior could be explained by an higher shrinkage of that mix, but unfortunately the authors did not report that data. Nevertheless it has to be noted that SCC5 has a very high coarse aggregate volume with respect to the other mix (800 $kg/m^3$ vs 180–240 $kg/m^3$).

### 4.2. Comparison with design codes

Among the different international codes and guidelines for the prediction and the calculation of shrinkage and creep effects in concrete structures [18,36–38,47], the following ones have been taken into consideration for comparison purposes with the outcomes of the experimental tests: CEB-FIP Model Code 90 (MC90) [38], EN 1992-1-1:2004 Eurocode 2 (EC2) [18], ACI 209.2R-08 (ACI) [36] and CEB-FIP Model Code 2010 (MC2010) [37].

The empirical predictive formula contained in these codes are based on an extensive experimental database, whose collection started in early eighties, [47], which considers only results obtained following standardized testing procedures for the measurements of shrinkage and creep, i.e.:

- Nominally identical specimens are made with the same concrete mix and exposed to the same curing conditions. One set is not loaded and it is used for shrinkage measurement, while the other one is generally loaded from 20 to 40% of the concrete compressive strength to determine creep.
- Stress induced strains are computed by subtracting the shrinkage strains, determined through the non-loaded specimens, from the total strains measured on the loaded specimens.
- Tests carried out on sealed specimens, with no moisture exchange on the external surfaces, are used to determine autogenous shrinkage and basic creep.

The predictive formula for both creep and shrinkage, contained in the above codes, are reported in Tables 2 and 3. The main differences among them consist in the adopted analytical expressions and in some of the parameters entering these expressions. However, some characteristics are in common: i) drying shrinkage and drying creep are bounded in time; ii) shrinkage and creep equations provide the corresponding strain

**Table 2**
Creep prediction models according to different codes.

| Code | Prediction Model for creep |
|---|---|
| CEB-FIP MC90 | $\varphi(t,t_0)=\beta_c(t-t_0)\cdot\varphi_{RH}\beta(f_{cm})\beta(t_0)$, $\beta_c(t,t_0)=\left[\frac{t-t_0}{\beta_H+t-t_0}\right]^{0.3}$<br>$\beta_H=150\left\{1+\left(1.2\frac{RH}{100}\right)^{18}\right\}\frac{h_0}{100}+250\le 1500$,<br>$\varphi_{RH}=1+\frac{1-RH/100}{0.46\sqrt[3]{h_0/100}}$, $\beta(f_{cm})=5.3/\sqrt{f_{cm}/10}$,<br>$\beta(t_0)=1/(0.1+t_0^{0.2})$ |
| CEN-EC2 | $\varphi(t,t_0)=\beta_c(t,t_0)\cdot\varphi_{RH}\beta(f_{cm})\beta(t_0)$, $\beta_c(t,t_0)=\left[\frac{t-t_0}{\beta_H+t-t_0}\right]^{0.3}$<br>$\varphi_{RH}=\begin{cases}1+\frac{1-RH/100}{0.1\sqrt[3]{h_0}} & f_{cm}\le 35\text{ MPa}\\ \left[1+\frac{1-RH/100}{0.1\sqrt[3]{h_0}}\alpha_1\right]\alpha_2 & f_{cm}>35\text{ MPa}\end{cases}$,<br>$\beta(f_{cm})=16.8/\sqrt{f_{cm}}$, $\beta(t_0)=1/(0.1+t_0^{0.2})$ |
| ACI209R-92 | $\varphi(t,t_0)=\frac{(t-t_o)^{0.6}}{10+(t-t_o)^{0.6}}\cdot\varphi_u$, $\varphi_u=2.35\cdot\gamma_{c,to}\gamma_{c,RH}\gamma_{c,vs}\gamma_{c,s}\gamma_{c,\psi}\gamma_{c,\alpha}$ |
| CEB-FIP MC2010 | $\varphi(t,t_0)=\varphi_{bc}(t,t_0)+\varphi_{dc}(t,t_0)$<br>$\varphi_{bc}(t,t_0)=\beta_{bc}(f_{cm})\beta_{bc}(t,t_0)$, $\beta_{bc}(f_{cm})=1.8/(f_{cm})^{0.7}$,<br>$\beta_{bc}(t,t_0)=\ln\left[\left(\frac{30}{t_{0,adj}}+0.035\right)^2(t-t_0)+1\right]$<br>$\varphi_{dc}(t,t_0)=\beta_{dc}(f_{cm})\beta(RH)\beta_{dc}(t_0)\beta_{dc}(t,t_0)$,<br>$\beta_{dc}(f_{cm})=412/(f_{cm})^{1.4}$, $\beta(RH)=(1-RH/100)/\sqrt[3]{0.1\frac{h_0}{100}}$<br>$t_{0,adj}=t_{0,T}\left[\frac{9}{2+t_{0,T}^{1.2}}+1\right]^{\alpha}\ge 0.5$ days, $\beta_{dc}(t_0)=1/\left(0.1+t_{0,adj}^{0.2}\right)$,<br>$\beta_{dc}(t,t_0)=\left[\frac{t-t_0}{\beta_H+t-t_0}\right]^{\gamma(t_0)}$, $\gamma(t_0)=1/(2.3+3.5/\sqrt{t_{0,adj}})$ |

List of symbols:
$t_0$: age of concrete at first loading [days].
$t$: age of concrete [days].
$f_{cm}$: mean compressive strength at an age of 28 days [MPa].
$RH$: relative humidity of the ambient environment [%].
$h_0=2A_c/u$: notational size of the member; with $A_c$ and $u$ being the section cross area in and the exposed section perimeter, respectively.
$\gamma_{c,to}$: parameter depending on $t_0$ and type of curing (moist or steam).
$\gamma_{c,RH}$: parameter depending on the relative humidity $RH$.
$\gamma_{c,vs}$: parameter depending on the notational size of the member $h_0$.
$\gamma_{c,s}$: parameter depending on the slump of the fresh concrete.
$\gamma_{c,\psi}$: parameter depending on the ratio of fine aggregate to total aggregate.
$\gamma_{c,\alpha}$: parameter depending on the air content.
$t_{0,T}$: age of concrete at first loading adjusted to consider the effect of elevated or reduced temperature.
$\alpha$: coefficient which depends on the type of cement.

**Table 3**
Shrinkage prediction models according to different codes.

| Code | Prediction Model for shrinkage |
|---|---|
| CEB-FIP MC90 | $\varepsilon_{cs}(t)=\beta_s(t-t_s)\varepsilon_{cso}$, $\beta_s(t-t_s)=\left[\frac{t-t_s}{350(h_0/100)^2+t-t_s}\right]^{0.5}$<br>$\varepsilon_{cso}=\beta_{RH}\varepsilon_s(f_{cm})$, $\beta_{RH}=1.55\left[1-\left(\frac{RH}{100}\right)^3\right]$,<br>$\varepsilon_s(f_{cm})=10^{-6}\cdot[160+10\beta_{sc}(9-f_{cm}/10)]$ |
| CEN-EC2 | $\varepsilon_{cs}(t)=\varepsilon_{cd}(t)+\varepsilon_{ca}(t)$, $\varepsilon_{cd}(t)=\beta_{ds}(t,t_s)k_h\varepsilon_{cd,0}$,<br>$\varepsilon_{ca}(t)=\beta_{as}(t)\cdot\varepsilon_{ca,\infty}$<br>$\beta_{ds}(t,t_s)=\frac{t-t_s}{t-t_s+0.04\sqrt{h_0^3}}$,<br>$\varepsilon_{cd,0}=10^{-6}\cdot 0.85\left[(220+110\alpha_{ds1})\exp\left(-\alpha_{ds2}\frac{f_{cm}}{10}\right)\right]\cdot\beta_{RH}$,<br>$\beta_{RH}=1.55\left[1-\left(\frac{RH}{100}\right)^3\right]$<br>$\beta_{as}(t)=1-\exp(-0.2t^{0.5})$, $\varepsilon_{ca,\infty}=10^{-6}\cdot 2.5(f_{ck}-10)$ |
| ACI209R-08 | $\varepsilon_{sh}(t,t_c)=\frac{(t-t_c)^{\alpha}}{f+(t-t_c)^{\alpha}}\cdot\varepsilon_{shu}$, $f=26\cdot\exp(0.142V/S)$,<br>$\varepsilon_{shu}=780\cdot 10^{-6}\gamma_{sh,tc}\gamma_{sh,RH}\gamma_{sh,vs}\gamma_{sh,s}\gamma_{sh,\psi}\gamma_{sh,c}\gamma_{sh,\alpha}$ |
| CEB-FIP MC2010 | $\varepsilon_{cs}(t,t_s)=\varepsilon_{cas}(t)+\varepsilon_{cds}(t,t_s)$, $\varepsilon_{cas}(t)=\varepsilon_{cas0}(f_{cm})\beta_{as}(t)$,<br>$\varepsilon_{cds}(t,t_s)=\varepsilon_{cds0}(f_{cm})\beta_{RH}\beta_{ds}(t,t_s)$<br>$\varepsilon_{cas0}(f_{cm})=-\alpha_{as}\left(\frac{f_{cm}/10}{6+f_{cm}/10}\right)^{2.5}\cdot 10^{-6}$, $\beta_{as}(t)=1-\exp(-0.2\sqrt{t})$<br>$\varepsilon_{cds0}(f_{cm})=10^{-6}[(220+110\alpha_{ds1})\exp(-\alpha_{ds2}f_{cm})]$,<br>$\beta_{RH}=1.55\left[1-\left(\frac{RH}{100}\right)^3\right]$, $\beta_{ds}(t,t_s)=\left(\frac{t-t_s}{0.035h_0^2+t-t_s}\right)^{0.5}$ |

List of symbols:
$t_s/t_c$: age of concrete at the beginning of drying.
$t$: age of concrete [days].
$f_{cm}$: mean compressive strength at an age of 28 days [MPa].
$RH$: relative humidity of the ambient environment [%].
$h_0=2A_c/u$: notational size of the member; with $A_c$ and $u$ being the section cross area in and the exposed section perimeter, respectively.
$\beta_{sc}$: coefficient which depends on the type of cement.
$k_h$: coefficient which depends on the notational size of the member $h_0$.
$\alpha_{ds1}$: coefficient which depends on the type of cement.
$\alpha_{ds2}$: coefficient which depends on the type of cement.
$f_{ck}$: characteristic compressive strength at an age of 28 days [MPa].
$\gamma_{sh,tc}$: parameter depending on $t_c$ and type of curing (moist or steam).
$\gamma_{sh,RH}$: parameter depending on the relative humidity $RH$.
$\gamma_{sh,vs}$: parameter depending on the notational size of the member $h_0$.
$\gamma_{sh,s}$: parameter depending on the slump of the fresh concrete.
$\gamma_{sh,\psi}$: parameter depending on the ratio of fine aggregate to total aggregate.
$\gamma_{sh,c}$: parameter depending on the cement content.
$\gamma_{sh,\alpha}$: parameter depending on the air content.

as function of time, concrete component size and changes in relative humidity; and iii) creep expressions depend on drying period before loading.

The information entering the expressions for creep and shrinkage prediction are related to: cement type; age of concrete when drying starts (usually taken as the age at the end of the moist curing period); age of concrete at loading; volume-surface ratio (or average thickness) and ambient relative humidity.

However, some differences can be observed between the three European codes [37,38,18] and the American one [36]. While in the formers information on cement type are provided in terms of compressive resistance and hardening velocity (the following three classes are considered: Class R, Class N and Class S); in the latter, more detailed information about cement content, fine aggregate percentage, slump and air content are required.

Fig. 11 shows the comparison, in terms of total strain and shrinkage strain for both NVC and SCC concrete mixes, between the experimental results and the corresponding predictions based on the above codes and assuming the experimental value of the modulus of elasticity.

Fig. 12 shows the comparison, in terms of total deformation for both concrete mixes, between the experimental results and the corresponding prediction based on the above codes, but assuming the design value of the modulus of elasticity, i.e. that computed on the basis of the code formula.

Based on the obtained results it is possible to draw the following conclusions:

- Model Code 90, [38], underestimates shrinkage strain for both NVC and SCC specimens.
- Model Code 2010, [37], underestimates the total strain measured experimentally, especially for SCC specimens. However, this result is consistent with the recommendation provided in this code, where it is claimed an underestimation of about 10–20% in case of SCC concrete materials.
- Thanks to the slump parameter which must be inserted into the predictive equations ACI209 [36] is capable to better discriminate between NVC and SCC behavior and provide a better prediction of both creep and shrinkage strains measured during experiments.
- All the codes considered in the present investigation overestimate the actual value of the modulus of elasticity and, for this reason, underestimate the total deformation occurring in the loaded specimens.

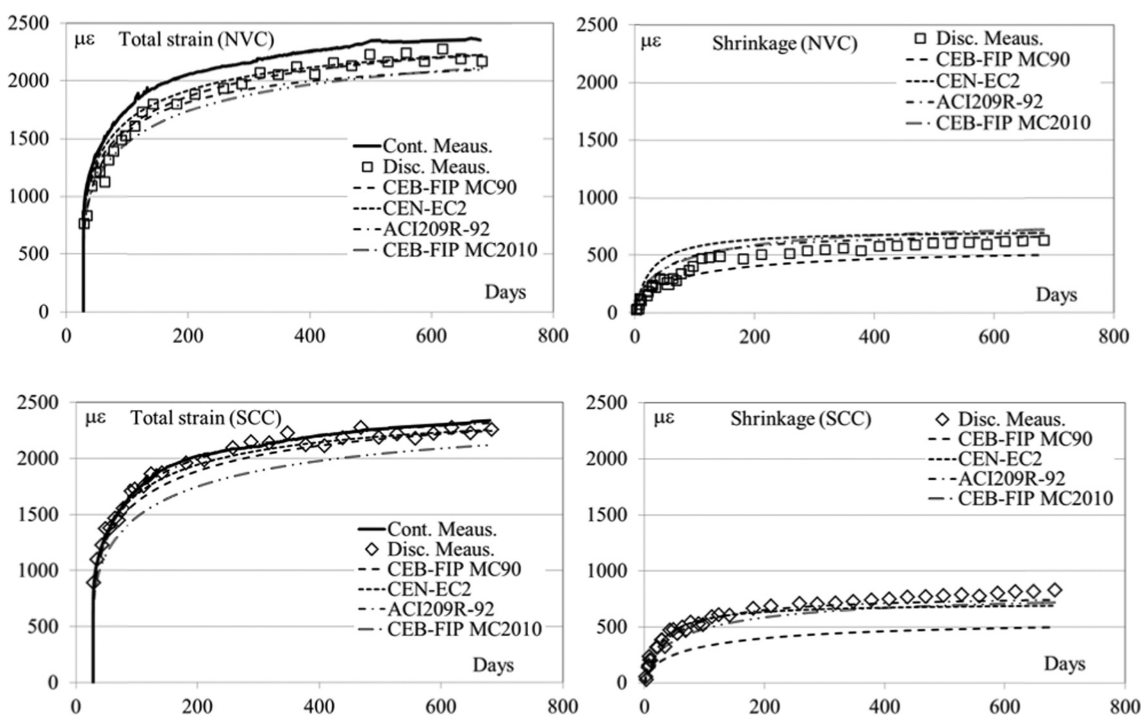


**Fig. 11.** Comparison between code predictions and experimental results assuming the measured modulus of elasticity.

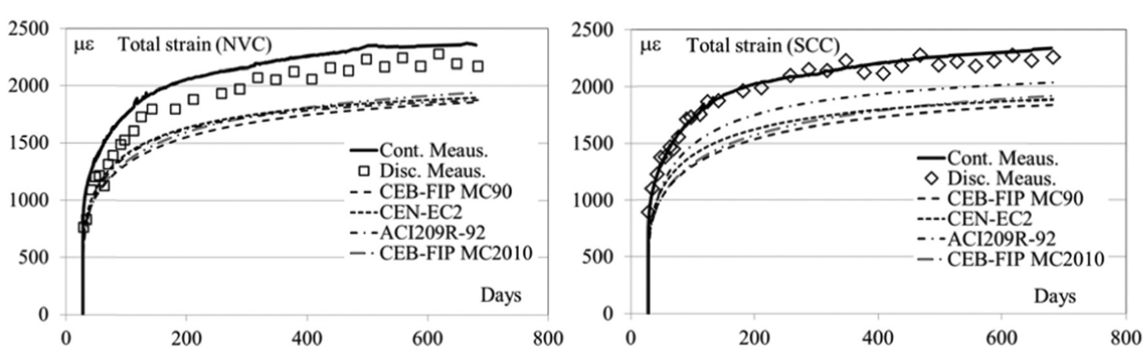


**Fig. 12.** Comparison between code predictions and experimental results assuming the modulus.

## 5. Conclusions

This paper presents a study comparing experimental concrete shrinkage and creep results of ordinary concrete (NVC) and self-compacting concrete (SCC) with the results of similar studies on creep behavior of SCC and with the values estimated by the most common codes (EC2 [18], CEB-FIB MC90 [38], CEB-FIP Model 2010 [37], ACI209 [36]).

The experimental results show that the tested SCC exhibits higher shrinkage with respect to NVC, while the total deformation of loaded specimens is similar, and as a consequence creep coefficient and creep compliance were higher in NVC than in SCC.

NVC and SCC specimens subjected to constant load seem to reach an asymptotic value at about 500 and 550 days, respectively.

The comparison of the experimental data with other researches confirm that the cement content, the type of filler and the paste volume play a major role in long term behavior of concrete.

The use of a large maximum aggregate size (22 mm) as well a large volume of coarse aggregate seems to have a beneficial effect on the long term behavior of concrete.

The ratio between cylindrical and cubic strength seems to be lower than the typical value, thus the characterization of SCC through cubic specimens requires further investigations.

The comparison of the experimental results and the code predictions showed that:

- All codes overestimated the elastic modulus, thus the total strain of loaded specimens is underestimated.
- By considering the experimental elastic modulus, EC2 [18] seems to well predict shrinkage and slightly underestimate the total strain.
- ACI209 [36] seems to better predict the differences between SCC and NVC thanks to the parameter related to slump, as well as the claim of MC2010 [37] that suggests an underestimation of about 10–20% of creep and of about 20% of shrinkage in case of SCC powder type, seems to be reasonable.

Summing up, to use SCC in structural applications it is advisable to select a mix-design with a known long-term behavior, or to use code provisions by assuming the experimental modulus of elasticity and to increase the total strain of about 10–20%.

Nevertheless for specific structures, sensitive to variations in creep/shrinkage (i.e. redundant structures) it is advisable to experimentally evaluate the long-term behavior according to MC2010 [37] suggestion.

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